The Reading Brain: The Canary in the Mind

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Abstract

The development of the seemingly simple cultural invention of reading alters the brain of each literate individual, propulses the intellectual development of the species, and provides human beings with a history of past knowledge as a foundation for future thought. Understanding how this happened in the species provides unexpected lessons for how children learn, how teachers teach, and how the brain learns anything new. Understanding the intrinsic plasticity of the reading brain circuit provides a cautionary tale for examining the cognitive impact of different media on how we read and how we think.

Literacy is transformative, for the potential of the individual and for the intellectual expansion of our species. In the process of its acquisition, literacy propels the development of new neuronal networks in the brain—particularly in evolving forms of connectivity between visual and language regions. The resulting circuitry creates a scaffolding for connecting perception and language to increasingly complex cognitive and affective processes. The *reading brain circuit* is one of the single most important epigenetic-based changes in the modern human brain and is the basis for the emergence of many of our most sophisticated intellectual skills.

Within this context, the increasing impediments to fully developed literacy require more focused attention by the scientific community. Some impediments are as old as writing itself, and some represent the unforeseen consequences of digital media. Thus the invention and the impediments are human-made and, in principle, can be redressed by the inventors.

The first impediments stem from the skewed relationship between literacy and privilege—whether in ancient Egyptian courts, medieval monasteries, or in today's world where 793 million people are nonliterate, most of whom live in poverty in sub-Saharan Africa and India. Further, at least 57 million children have no school and will never become literate. Access to

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schools, however, is no assurance of literacy. In sub-Saharan Africa, children attending school for 5 years have a 40% chance of being illiterate. Millions more around the world are, for all purposes, functionally illiterate due to inadequate schools and inappropriate instruction. Most of these individuals will never contribute their full potential to society.

In essence, therefore, a variant of Stanovich's "Matthew Effect, " where the "rich get richer and the poor poorer", governs the reciprocal relationship between poverty and literacy today on every continent. In the United States, arguably the most privileged nation, only one-third of American children reach a level of reading proficiency necessary for higher levels of academic achievement linked to economic security. Further, more than half U.S. children who are Latino or African American never reach the most *basic* level of literacy. Such figures virtually ensure that the well-documented achievement gaps will persist and deepen, with consequences for the intellectual growth and socioeconomic possibilities of the nation and the individual, whether in rural Alabama or in urban Los Angeles. Buttressing these conclusions, the Council on Foreign Relations stated: "Large, undereducated swaths of the population damage the ability of the United States to physically defend itself, protect its secure information, conduct diplomacy, and grow its economy."

If all students in low-income countries acquired full literacy skills, 171 million people could be lifted out of poverty, resulting in a 12% drop in world poverty. These national and global realities require intensive application of research—some that exists, and some that needs to be developed and will be described here.

An emerging but much less understood impediment to full literacy concerns the effects of the transition from a print-based to a digital-based culture, particularly on the young. Reading is a cultural invention and, therefore, possesses no genetically pre-wired circuit that unfolds with contact with the environment, as in the case of language or hearing. Consequently, the reading brain is doubly dependent in its formation: first, it requires considerable environmental supports; second, it *adapts itself* to requirements in that environment—from the writing system and type of instruction, to the characteristics of the *medium*. The significance of this adaptational malleability is that the characteristics or *affordance*s of the digital medium are changing the reading circuit, particularly in the development and use of the most highly elaborated processes undergirding full literacy.

In this essay, I use knowledge about the reading brain's emergence to address key questions related to these impediments. First, what are the developmental implications of knowledge about the reading brain circuit for the youngest readers? Specifically, how does the first circuit move from the simple decoding of information to sophisticated acts of cognition in expert readers? Second, what are the ramifications of a plastic reading circuit in a digital-based culture? What are the implications of immersion in digital reading—for children's development, for the democratization of knowledge, and for the expansion of literacy in the twenty-first century? These areas represent critical trends of research with the potential to change how we read and how we think and to render obsolete the Matthew effect on literacy.

HOW THE READING BRAIN EMERGED

In all likelihood, our species has possessed the same basic brain for approximately 50,000 years. During this time, we invented many things—from wheels and physical tools, to cave drawings and flying buttresses in cathedrals, to the particle accelerator and the digital culture. The capacity to invent illumines one of the protean features of the brain's design: its ability to go beyond genetically programmed networks (e.g., vision and language) to create new circuits for increasingly sophisticated functions. These circuits involve new connections among older networks and an ingenious design principle: *neuroplasticity*.

Reading's acquisition highlights two ways that neuroplasticity helps humans acquire new cognitive functions. First, reading necessitates the creation of novel connections among some of the structures underlying language, perception, cognition, and emotions. In this sense, literacy rewires the brain of every reader.

Second, reading's circuit reshapes the smallest building blocks of that wiring, the neuron itself and neuronal working groups that carry out all human activities. Neuroscientists Stanislas Dehaene and Laurent Cohen use the term *neuronal recycling* to describe how reading repurposes visual cortex neurons originally used to recognize faces and objects. They describe how neuronal working groups in visual and occipital-temporal areas are "recycled" to recognize letters, letter patterns, morphemes (e.g., roots, prefixes, suffixes), and familiar words with absolute precision and speeds approaching automaticity.

Written language, therefore, provides an example of how plasticity can be applied at both macro and micro levels to functions closely related to the original purposes of neuronal working groups. In the case of literacy, working groups for recognition of visual features within faces and objects are recycled for recognizing the smallest features of letters and symbols.

And this changed our species. A reading circuit emerged that enabled not only rapid symbol recognition but also more elaborated connections among cognitive, language, and affective networks. Over time, these networks provided literate humans a platform like few others for the development of new thought.

From this view, the study of the reading brain helps us to understand how the brain learns *anything* new. It is a twenty-first century cognitive neuroscience analog to the earlier use of the squid's long axons to study the central nervous system.

In sum, the development of this seemingly simple cultural invention alters the brain of each literate individual (Carreiras *et al*., 2009), propulses the intellectual development of the species, and provides human beings with a history of past knowledge as a foundation for future growth. Understanding how this happened in the species provides unexpected lessons for how children learn and how teachers teach.

WHAT THE READING BRAIN HAS TO TEACH

> There is nothing that a little bit of science cannot help. Parents and educators must have a better understanding of what reading changes in a child's brain … I am convinced that increased knowledge of these circuits will greatly simplify the teacher's task
>
> Stanislas Dehaene (2009)

The first implication of a plastic reading brain is that there is no prototypical circuit that will emerge in the way that vision or language develops—with a small environmental nudge. Because written language was invented and not inherited, there are neither pre-dedicated genes nor universally prescribed structural regions only activated for reading. Rather, as alluded to, different reading circuits will form, based on environmental factors like the writing system, the form of instruction, and of most import currently, the medium. The upshot is that each new reader has to learn to build his or her own reading circuit with instruction from the generation before and supported practice till the circuit becomes automatic.

Therein lies many an abrasive rub. As stated, 57 million children have no schools, and another 150 million have inadequate schools. This means that 200 million members of the next generation will have no reading circuit, or at most a skeletally impoverished one—capable of basic decoding but insufficient for more sophisticated intellectual processes. The latter reality describes the learning trajectory for uncounted numbers of children in the United States who may have adequate schools but inappropriate instruction for their individual needs. These children fill the ranks of the droves of reading failures reported in the United States by national and international indices.

There are both environmental reasons for these failures (e.g., inequality and poverty, dual-language learning issues, poor instruction) and neurobiological ones like dyslexia. An understanding of the basic principles underlying the formation of the reading brain circuit contributes to a new conceptualization of all of these failures, and a new approach to their intervention. First, the circuit requires that each *component part* of the circuit be developed sufficiently so that neuronal repurposing can occur. For example, pre-reading children require multiple exposures to the letters or symbols of their writing system, to the sounds or phonemes (smallest units of sound) in their language, to basic cognitive concepts that form their background knowledge, and to a repertoire of words that reference their world. These elements comprise the *representations* that make up the major components of the young circuit: that is, the orthographic, phonological, cognitive (attentional, memory, and conceptual), and semantic processes. Only when the representations in these individual processes have been sufficiently developed can the environment's instruction help the individual child connect the component parts to form a nascent circuit and learn to read.

Thus the first, and potentially most important, lesson of the young reading brain is that the circuit parts be fully nurtured and developed before the child ever tries to learn to read. Whether in Ethiopia, where my work with nonliterate children began, or in rural parts of the United States where it continues, the reading circuit begins its slow reshaping of the brain long before any Kindergarten or First Grade teacher begins to teach—through continuous exposures to words, sounds, letters/symbols, and concepts. A new direction in brain imaging research in pediatric neurology shows how effective the simple practice of a parent reading daily to the child can be in providing these exposures and advancing the development of speech and language. Hutton and his colleagues demonstrate that the quality of a mother's language interactions while reading to her child is correlated with heightened activation of the speech, language, and attentional areas in the young child's frontal and temporal lobe regions. While still in its early stages, this research buttresses the work of the pediatrician organization, Reach Out and Read, in which parents are given developmentally appropriate books at every well visit in the first years. Further, it provides a research basis for the critical importance of early language development.

The reality is that many parents and even preschool teachers are unaware of how essential exposure to oral and written language is to children's later development, even for young infants who have no expressive language. New forms of imaging in pediatric neurology reveal that receptive language areas are already forming in two-month-old infants. The books of childhood, the rhymes of Mother Goose, and the stories of every culture furnish the sounds of oral language, the symbols and conventions of written language, the concepts of the culture, and a vocabulary of words unique to text. Without such a well-established foundation of language and concepts in the preschool years, reading's circuitry will take longer to develop, decoding will be more difficult to learn, and there will be less opportunity for cognitive elaboration if decoding remains laborious. Ongoing research, which is little addressed in the formation of teachers, indicates that a failure to develop *any* of the component building blocks can impede reading acquisition and will require additional targeted instruction by the educational system.

The second lesson from the circuit's formation is that learning to decode fluently is cognitively far more complex than previously understood, with the consequence that some children never go beyond basic levels of literacy. A common misconception is that reading is a natural process that unfolds like language when immersed in reading environments. With the exception of fictional characters like Kit in *To Kill a Mockingbird* and real outliers like Jean Paul Sartre (who taught himself), the typical reading brain requires more direct support through explicit instruction and ample practice in forming the connections among the component parts of the circuit. This is not universally understood.

For over half a century, educators have differed radically over which methods of instruction are best for learning to read. The crux of the conflict revolves around whether the young reader should be *directly* taught by an instructor, or whether the child should *induce* the principles of learning to read by immersion in the materials given. Decades of research demonstrate that approaches that explicitly emphasize an awareness of the phonemes of the language and their correspondence to particular letters provide the best foundation for learning the semi-systematic rules of decoding words in English. Advocates of inductive or *whole-language* methods, however, continue to adhere to the notion that children learn best if they *infer and construct* the rules of decoding themselves through exposure to literature and stories, thus building concepts and vocabulary. Memorably described by Seidenberg (2017) as "theoretical zombies that cannot be stopped by conventional weapons such as empirical disconfirmation, leaving them free to roam the educational landscape," whole-language methods continue to dominate practice in many parts of the United States and Australia.

As a researcher, my approach to this question has been straightforward: what methods have evidence for efficacy, for whom, when, and under what conditions? The most difficult consequence of the twentieth century instructional debates is that, despite essential emphases on words and stories, the whole-language or inductive methods are insufficient to meet a large number of children's needs, a conclusion reached by multiple empirical studies. It is here that cognitive neuroscience research may make an important contribution to educational practice.

As alluded to, in the reading circuit's ideal development, each of the components requires extensive exposures and environmental support for them to develop before and after reading instruction begins. These emphases promote the development of (i) visual recognition of letters/letter patterns/morphemes, (ii) high-quality representation of phonemes, (iii) connections between letters and sounds, (iv) growth of semantic and syntactic knowledge, and (v) the ultimate connections among all systems in reading text (e.g., stories, narrative). Such a multicomponent developmental conceptualization of the reading brain's formation dictates a more multidimensional approach to reading instruction and intervention and a more nuanced understanding of reader differences over their development. Specifically, this approach includes phonics-related principles from the outset, alongside systematically integrated vocabulary and conceptual development at the word and story (text) level. In essence, therefore, an approach based on the reading circuit's formation integrates core emphases of phonics and whole language methods by providing explicit emphases on *all* of the cognitive, perceptual, and linguistic processes *and their connections* before, during, and after acquisition.

The broadened foci within this conceptualization are particularly important for addressing various reading impediments in children, because the multidimensional emphases can be more easily tailored to children's specific needs. Indeed, differences in reading profiles in American classrooms have grown exponentially, with many children having combinations of dual-language-learning needs, impoverished backgrounds, and/or special needs like attentional deficits, dyslexia, and autism (Ozernov-Palchik *et al.*, 2016). As many as 40–50% of the children in some urban schools require differential instruction, but rarely receive it. Most recently, cognitive neuroscience-based research by Ozernov-Palchik, Gabrieli, Gaab, and our group has demonstrated that six core literacy profiles of children can be predicted as early as Kindergarten: two with average to superior reading related precursors, one with environmental and/or orthographic-related issues in letter-sound knowledge, one with more speed of processing issues indexed by naming speed, one with phoneme-based issues, and one (the most severe) with multiple deficit areas.

The importance of this direction of research for literacy development is potentially game-changing. First, more differential prediction lays the groundwork for far earlier, more *targeted* intervention. As Gaab states, the current paradox in dyslexia research is that most diagnoses of dyslexia occur in second and third grades, despite the fact that earlier intervention achieves better results. Considerable evidence by our group indicates that the more intensive and earlier that intervention begins, the better the effects on reading performance. Second, early prediction can help prevent the insidious social–emotional sequelae of reading failure. For example, simpler impediments can sometimes be ameliorated through prompt and specific instruction. Across all children, early diagnoses help them, their teachers, and parents to better understand that the child is neither lazy nor unintelligent, two of the most common errors made with children with undiagnosed dyslexia that often contribute to social–emotional difficulties. Third, more targeted prediction helps educators to avoid the continued use of inappropriate, already failed forms of intervention by providing far more individualized instructional emphases aimed at the particular profile as it changes with development.

An important research direction in early targeted intervention involves studying the effects of single- and multi-component interventions for children with dyslexia and early reading impediments. In a series of NICHD-funded, randomized treatment–control studies, our group designed different interventions based on various combinations of components of the reading brain. These studies demonstrated the efficacy of a multidimensional approach for atypical developing children, particularly when the intervention begins early and intensively. The advantage of these multidimensional approaches is that they encompass a full range of emphases that can be utilized in instruction in various modes of intensity, according to different children's changing needs over development. Similar comparative research for dual-language readers needs to be conducted, but anecdotal evidence supports the utility of this approach for young Spanish-speaking readers who are learning to read in English.

The foundational knowledge about the reading brain that informs this recent research on intervention should also inform decisions about instructional methods and ongoing assessments for typical readers with their naturally occurring heterogeneity over time. In this way, many children who fail to go beyond basic decoding because of past one-size-fits-all methods will receive more developmentally tailored instruction to help them achieve the deeper forms of cognition propelled by expert literacy.

The other critical lesson that can be derived from the formation of the reading circuit is that the fluency (or speed of processing) of each component part and of their connected integration is essential for the reader to connect decoding to deeper thinking processes. This is the cognitive prerequisite for what reading researcher Jeanne Chall called the move from *learning to read to reading to learn*. This is also the mentally arduous impediment that many children in the early grades never conquer. They remain arrested in laborious decoding, through insufficient development and/or fluency in one or many of the component parts of the circuit. It is the child's version of an intellectually stunted life-sentence.

There are as many sources as consequences. The cited national and international statistics reflect what happens when children fail to cross the critical gap between decoding and deeper forms of reading. One of the more important directions of future research is to figure out how the great majority of our children can achieve sufficient fluency in the early grades, before the "double whammy" of Grade Four is encountered: that is, teachers who were never instructed to teach reading and who assumed that children would enter Grade Four as able readers, and the increases in text complexity, in word and sentence length, in syntactic density, and in conceptual demands. Only children who are fluent before they end Grade Three and Four will have the prerequisites to go beyond a skeletal reading circuit and reach the cognitive platform that is given in the fully elaborated reading brain circuit.

WHAT THE READING BRAIN HAS TO LEARN TO BECOME AN EXPERT

> We feel quite truly that our wisdom begins where that of the author leaves off … But by a singular and moreover providential law … (a law which perhaps signifies that we are unable to receive the truth from anyone else but must create it ourselves), that which is the endpoint of their wisdom appears to us as but the beginning of our own …
>
> Proust, "On Reading" (1906/1971)

Proust could not have written a more fitting literary description of the cognitive, linguistic, and affective complexity that opens when the reader learns to read fluently enough to allocate time to comprehension. From other perspectives, these complex processes underlie what literary critics call *close reading*, or *slow reading*, or what I describe as *deep reading*. Although neither exclusive nor linear in nature, deep reading processes involve dynamic interactions among multiple processes like *imagery* and the retrieval of *background knowledge*; *analogical and inferential* processes that lead to *critical analysis*; *affective* processes like perspective-taking and empathy; and on occasion the *generative* processes leading to *insight*, the pinnacle of deep reading and what Proust presciently described as the " endpoint of their {author's} wisdom and the beginning of ours".

From a developmental perspective, *deep reading* begins like all aspects of reading with the development of individual linguistic, cognitive, and affective processes and then the gradual connection of these processes to the basic reading circuit. The essential requirements in this process are two: first, that decoding becomes fluent enough to allow the young reader time (in ms) to think more deeply about what is read; and second, that the developing reader learns over time (in years) to connect the meaning(s) from the text to increasingly complex deep reading processes. Thus the temporal dimensions necessary for deep reading are several. The developing readers must read fast enough to think not only about what the text provides in content, but also about what insights this activates in themselves. As Proust determined long before cognitive neuroscience emerged to study it, the very apex of the reading act is the formation of these insights, an attainment that is not "a given" at any age or in any individual.

Understanding the "neural signature of insight" is a work in progress in neuroscience and in some of my own work. In a meta-review of varied imaging studies on insight and creativity, Dietrich and Kanso (2010) wrote: "An insight is so capricious, such a slippery thing to catch *in flagrante*, that it appears almost deliberately designed to defy empirical inquiry. To most neuroscientists, the prospect of looking for creativity in the brain must seem like trying to nail jelly to the wall." At one point in their review of all the available imaging studies, Dietrich and Kanso expressed the prose equivalent of hands thrown up in the air: "it might be stated that creativity is everywhere!" (p. 838).

The perspective of philosopher Charles Taylor provides a wholly different view of the generative dimension at the heart of language, both oral and written, that may prove useful to the study of insight. Based on the work of nineteenth century German scholar Wilhelm von Humboldt, Taylor emphasizes the *generative* dimension within language that compels human beings to strive towards more refined and precise articulations of their thoughts. Humboldt wrote that within language there is a continuous "feeling that there is something which the language does not directly contain, but which the mind/soul, spurred on by language, must supply; and the drive, in turn, to couple everything felt by the soul with a sound." (quoted in Taylor, 2016). Taylor uses Humboldt's conceptualization to assert that "possessing a language is to be continuously involved in trying to extend its powers of *articulation.*" The intrinsic drive to articulate a concept more fully with greater depth is key to Taylor's argument that language is a deeply human project, and is akin to linguist Ray Jackendoff's assertion that language is a set of "peepholes" on thought and meaning.

I argue that this ineffable *drive* within language's core is also key to understanding the deep reading brain, and vice versa. I conceptualize the entirety of the deep reading processes as part of the intrinsically human drive toward the pursuit of ever deeper levels of understanding and our efforts to articulate this. Further, like Vygotsky, I believe that the very act of trying to articulate what we understand advances thought.

Finally, based on findings by Dietrich and Kanso, I believe the existing evidence on insight—that the processes involved in this drive towards meaning and creativity appear "everywhere"— no coincidence. Deep reading involves the use of multiple complex networks of cognitive, affective, and linguistic processes in the propulsion to find and generate our best thoughts. In so doing, deep reading activates both hemispheres, four lobes, and all five layers of the brain: it might be stated that *deep reading* "is everywhere".

Thus, within this biological and philosophical context, the expert deep reading brain is both the consummation and the reflection of the brain's design principles that permit phenomena like new circuits to emerge. We are programmed to go beyond ourselves through our brain's basic design, and written language reflects this deeply entrenched drive between what we are given and what we create ourselves.

WHAT THE READING BRAIN MAY LOSE IN THE DIGITAL CULTURE

> No one medium can do everything. Every medium has its costs and weaknesses; every medium develops some cognitive skills at the expense of others. Although the visual capabilities of TV, video games, and the Internet may develop impressive visual intelligence, the cost seems to be to deep processing: mindful knowledge acquisition, inductive analysis, critical thinking, imagination and reflection. (Greenfield, 2009, p. 71)

Everything I have written to this point is undergoing radical change, the correlative of the costs Greenfield describes. With no genetic program, the plastic reading circuit adapts to the dominant medium. In an earlier book, I cautioned that the affordances of digital reading could change the way we read and potentially how we think because of different cognitive demands on attention, memory, and the allocation of time to analytical and reflective processes. Our culture has now almost completed its transition from a literacy-based to a digitally based culture with concomitant changes to attention, memory, and the way many of us now process what we read. As reading researchers describe, skimming is the norm, with readers skimming from the top line in an F or Z pattern to the last line, with sporadic word-spotting in between. Other scholars describe these patterns as characterizing a new "hyper-reader", whose attention is constantly distracted, with negative effects on sequencing details and, more ominously, comprehension.

These issues are compounded because how we read and comprehend has reciprocal effects on how we process the glut of information and consolidate knowledge derived from it. Thus we enter what I refer to as the "digital reading chain," which has its beginnings in our evolutionary, reflex-based need to attend to novel stimuli. A reflex that once protected us from predators now confuses attention, rather than focuses it. We continuously attend to a bombardment of novel stimuli and distractions in the digital environment, which affects how much we read, how we read, the characteristics of what we read, and finally, what is written. We are all changed along this chain.

We need only examine our own attentional span, multitasking, memory, and present immersive reading experience to recognize the changes in the *cognitive patience* we expend toward what we read. These changes reflect the amount of time we may no longer allocate to inference, critical analysis, and insight. The reading brain circuit requires time in several dimensions: time for the initial formation of deep reading operations measured in *years* of gradual elaboration and development, and time in *milliseconds* in what the expert reader allocates to the multiple components that contribute to deep reading. From a physiological perspective, for those who have become some version of the "hyper-reader", the neuronal pathways for their reading circuits have more than likely come to match the associated characteristics of the digital medium: fast, multitask-oriented, and less suited for reflective functions. Current research about how children today are affected by screens shows how thin the semipermeable membrane is between the medium and children's often distracted reading with downstream effects on comprehension.

The cognitive differences between our culture's two modes of reading (print and screen), however seemingly subtle to the reader, require far more in-depth research. Increasing studies demonstrate substantive changes in the attention span and working memory of adults today, when compared to a decade ago. Given the significant role of attention and memory within the reading circuit, we need to understand how we are allocating time to each of the deep reading processes and what may atrophy if we neglect them. Specifically, given the increased reliance on external platforms of knowledge, will digital readers change in their consolidation of new information into memory, which is their repository of background knowledge? If so, will less developed internal platforms of knowledge alter the development and deployment of analogical processes used to connect past knowledge with new information? Will the use of inferential skills for understanding new information change with more superficial, skimming reading modes? Given that typical young adults are distracted on average 27 times an hour, what are the effects of multitasking and distraction on focused attention and critical analyses?

The very plasticity of the reading brain gives reason for alarm *and* hope (e.g., Poldrack on multi-tasking in digital natives; and Mangen (Mangen, Walgermo, & Bronnick, 2013) on differential effects of mediums on sequencing information and comprehension). Given the present often contradicting studies, a more systematic understanding of the effects of different media is critical if we are ensure that future generations are not characterized by a short-circuited reading brain, over-dependent on external knowledge access, with underdeveloped deep reading processes, formed till now with slower print mediums.

HOW THE DIGITAL READING BRAIN CAN ADVANCE LITERACY

Regardless of perspective, if humans are to preserve what is arguably the apex of cognition in the present reading circuit at the same time that the species acquires essential digital-based skills, we must use the full sum of science and technology to examine our goals and their implications with singular vigilance. Years ago, Ong wrote that the most difficult challenge *and* opportunity a society can face occurs when it is "steeped in two mediums". The careful development of what I have described elsewhere as a *biliterate brain* represents one example of the thoughtful use of two media.

Other critical research directions require the joint attention of science and society. For example, our research collaborative (CuriousLearning.com; Wolf, 2007; Wolf & Gottwald, 2016) is investigating whether digital devices can increase literacy in nonliterate populations with either no schools or teachers, or inadequate schools (e.g., teacher/student ratio of 1:60–100). A transformative advantage of digital culture is the potential to provide broader access to knowledge and communication across cultures: that is, *the democratization of knowledge.*

In our initiative, we use research from cognitive neurosciences, child development, and education to develop and/or curate software content based—like our dyslexia interventions—on reverse engineering the reading circuit (see RAVE-O description in Lovett *et al.,* in press). An evolving "app map" based on this developmental knowledge is used to curate existing apps and to help develop new apps. An open-source platform has the capacity to assess various aspects of usage and to add ongoing forms of assessment to evaluate efficacy and engagement. Ongoing deployments are in Ethiopia, South Africa, Uganda, India, and Peru. First evaluations in Ethiopia demonstrated significant gains in vocabulary in English, in letter knowledge, and in precursors of literacy. In Uganda, children in urban preschools are successfully using the digital devices to acquire similar precursors. In newer deployments with indigenous populations in Australia and with children with limited access to preschools in rural Alabama and Georgia, we seek to understand whether these devices can provide multiple exposures to the varied aspects of language and print, thus developing component parts of the reading circuit.

The preliminary success of our Ethiopian deployments led to more extensive initiatives in global literacy through the first X-Prize for Literacy. Participants are investigating new software for promoting literacy in Tanzania. Such initiatives will propel research, content, and technological advances, as open-source platforms steadily increase world literacy and decrease world poverty.

Summary

Understanding the emergence of the reading brain circuit underscores how neuroplasticity renders it vulnerable to atrophy or loss of sophisticated cognitive and affective processes—from critical analysis and empathy to reflection. It simultaneously highlights how adaptational malleability in digital culture bestows an extraordinary potential to democratize knowledge in ways heretofore impossible. Understanding the cognitive impact of different mediums on the reading circuit represents a critical direction for guiding optimal learning and teaching. The careful fashioning of the future reading brain is one of the most important legacies we can leave our children. For, the ultimate lesson of the reading brain is that it is *the canary in the mind*.

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