REVIEW ARTICLE

Language and reading development in the brain today: neuromarkers and the case for prediction☆

Augusto Buchweitz

School of Letters, Instituto do Cérebro do Rio Grande do Sul (Inscer), Pontifícia Universidade Católica do Rio Grande do Sul (PUCRS), Porto Alegre, RS, Brazil

Abstract
Objectives: The goal of this article is to provide an account of language development in the brain using the new information about brain function gleaned from cognitive neuroscience. This account goes beyond describing the association between language and specific brain areas to advocate the possibility of predicting language outcomes using brain-imaging data. The goal is to address the current evidence about language development in the brain and prediction of language outcomes.
Sources: Recent studies will be discussed in the light of the evidence generated for predicting language outcomes and using new methods of analysis of brain data.
Summary of the data: The present account of brain behavior will address: (1) the development of a hardwired brain circuit for spoken language; (2) the neural adaptation that follows reading instruction and fosters the ''grafting'' of visual processing areas of the brain onto the hardwired circuit of spoken language; and (3) the prediction of language development and the possibility of translational neuroscience.
Conclusions: Brain imaging has allowed for the identification of neural indices (neuromarkers) that reflect typical and atypical language development; the possibility of predicting risk for language disorders has emerged. A mandate to develop a bridge between neuroscience and health and cognition-related outcomes may pave the way for translational neuroscience.
© 2016 Sociedade Brasileira de Pediatria. Published by Elsevier Editora Ltda. All rights reserved.

PALAVRAS-CHAVE
Desenvolvimento
da linguagem;
Imagem cerebral;
Predição

Desenvolvimento da linguagem e da leitura no cérebro atualmente: neuromarcadores e o caso de predição

Resumo

Objetivos: O objetivo deste trabalho é apresentar um relato sobre o desenvolvimento da linguagem no cérebro utilizando as novas informações sobre função cerebral obtidas na neurociência cognitiva. o relato vai além da descrição da associação entre linguagem e áreas específicas do cérebro e defende a possibilidade de predizer os resultados de linguagem por meio de dados de imagens cerebrais. O objetivo é tratar das evidências atuais sobre desenvolvimento da linguagem no cérebro e abordar a possibilidade de predição de resultados de linguagem.

Fontes: Estudos recentes serão discutidos em face das evidências geradas pela predição de resultados de linguagem e pelo uso de novos métodos de análise de dados cerebrais.

Resumo dos dados: Este relato de comportamento cerebral abordará: (1) o desenvolvimento de um circuito cerebral de linguagem falada; (2) a adaptação neural que segue a instrução da leitura e incentiva a ''inserção'' de áreas de processamento visual do cérebro no circuito de linguagem falada; e (3) a predição do desenvolvimento da linguagem e a possibilidade de uma neurociência translacional.

Conclusões: As imagens cerebrais permitiram a identificação de índices neurais (neuromarcadores) que refletem o desenvolvimento da linguagem típico e atípico; surge a possibilidade de prever o risco de disfunções de linguagem. A responsabilidade de desenvolver uma ligação entre neurociência e resultados relacionados a saúde e cognição pode abrir o caminho para a neurociência translacional.

Introduction

One of the key challenges for the neurosciences is to become faster and more effective at producing evidence that transforms health and education-related practice. Neuroscientific studies of neuronal markers hold promise for more successful health and education policies. The obstacles to making predictions from brain data involve producing more generalizable, robust results; establishing communication channels with education and healthcare decision-makers and professionals; and addressing ethical issues that arise from making such predictions. The present article focuses on a specific type of evidence: functional brain data obtained from noninvasive brain imaging to predict developmental and clinical outcomes. Recent studies will be discussed in the light of the evidence generated for predicting language outcomes and of using new methods of analysis of brain data.

With the advent of magnetic resonance imaging (MRI) and its varied functional and structural procedures, studies of the brain mechanisms that underpin cognition and psychiatric disorders have flourished.[1] Studies using functional MRI (fMRI) have unveiled specific neural circuitry and mechanisms for language acquisition, language disorders, and language-related processes.[2–4] Language development has been shown to be amenable to investigation by MRI procedures.

Research on the brain's structural and functional indices that predict language outcome[5–11] may be an effective means to translate new evidence into applications.[4–12] However, the influence of the research outside the scientific community appears to fall short of its promise.[1] The production of generalizable models of clinical and educational outcomes based on these indices (neuromarkers) is an exciting possibility for changing the way health and education-related decisions benefit from brain imaging. A recent review[13] advocated the application of brain measures in the prediction of outcomes in several fields, including education and learning; health-related behaviors and responses to treatments; and relapse for alcohol, smoking, and drug addiction. Prediction was defined as producing generalizable models that effectively identify outcomes in out-of-sample individuals; in the interest of the present article, this would mean establishing neuromarkers that can be applied to more diverse populations outside the smaller-sample brain imaging studies.[13] Prediction, in this broad sense, is the ultimate test of a neuromarker after passing the test of reliable within-subject and in-sample predictions.

Noninvasive brain imaging measures: fMRI

The present article focuses on evidence from fMRI investigations of language development. This technique identifies changes in metabolism and oxygen levels in the brain.[14,15] Though the increase in metabolism is not a direct measure of neuronal activity, the blood-oxygen level dependent (BOLD) signal acquired during fMRI procedures reflects neural responses: there is a correlation between electrical discharges from neurons and the BOLD signal.[16,17] Other MRI procedures, such as diffusion-tensor imaging, used for investigations of white matter pathways, are increasingly being used in multimodal studies of language processes, disorders,

and development.[13,18–21] Other methods, such as event-related potentials, have also effectively predicted language outcomes: neonatal event-related potentials (as early as 36 h after birth) were predictive of language outcomes at 8 years of age.[22] Multimodal investigations that combine procedures eliminate the shortcomings of the different procedures.[23] A more in-depth discussion of multimodal investigation and methods is beyond the scope of the present article.

Spoken language development: a resilient process, its milestones, and hardwired brain circuitry

Early language development and emerging communication abilities are fundamental for the development of cognitive and social skills.[24] Language development is one of the key factors associated with the development of mental capital; this means ensuring that each person is given the chance to achieve their full cognitive potential, and is allowed to prosper and flourish within modern society.[25]

The United States Committee on Integrating the Science of Early Childhood Development produced an evidence-based report on early brain development, language, socialization, and self-regulation. In the words of the report: spoken language is resilient, literacy is fragile.[24] These two key aspects of oral and written language development, resilience and fragility, have been investigated in the light of brain imaging. There are language milestones (behavioral markers) associated with neural signatures of language. The milestones provide evidence that helps establish predictive brain–behavior relationships for language.
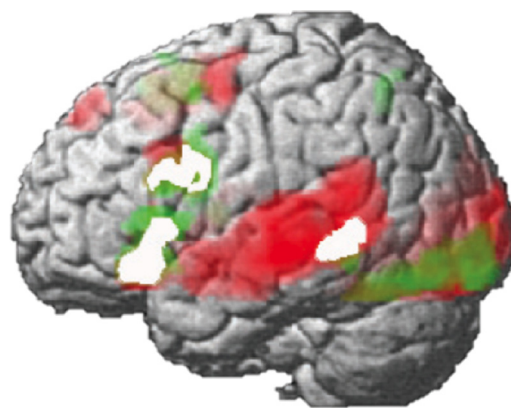
Spoken language develops without instruction. The process of development occurs in almost all children despite economic and social hardships, as well as lack of instruction (but such hardships influence qualitative and quantitative aspects of language and cognitive development).[24,26–28] The brain circuits that develop for spoken language are hardwired in the brain. The components of the language circuitry are associated with levels of auditory comprehension processes; the key centers and processes include: (1) the primary auditory cortex, which processes raw auditory information; (2) the posterior temporal and inferior parietal cortices, which process the systematic organization of word sounds; (3) the middle temporal cortex, which is associated with accessing word meaning; (4) and the inferior frontal cortex, which processes the structure of language. Over the past 25 years, noninvasive brain imaging has provided robust and replicable evidence about the brain circuits that develop for spoken language. It is worth mentioning that the brain areas involved depend on the granularity of the language process being investigated.[2,3,9,29,30]

At times there are delays in oral language development. The age at which a child begins to speak is a behavioral marker of such delay. Children usually produce their first words between 10 and 15 months of age. A delay in speaking indicates atypical language development, and is one of the indicators of risk for reading disorder.[31–33] Language milestones such as age at speaking can be evaluated in terms of the typical neural circuits that develop in the child.

A recent study of early and late talkers identified cortical and subcortical markers of children who spoke their first words at 1.2 years (early) *versus* those who spoke at 2.5 years (late).[34] In addition to better performance in language tests at 8 years of age, early talkers (also at 8 years of age) showed more activation in subcortical structures associated with the learning of rule-based systems (putamen and thalamus); these subcortical structures are at the basis of learning new linguistic skills.[35,36] Early milestones as simple as uttering two to three word sentences are strong indicators of language outcome, and the effects of age at speaking are associated with markers of brain development. Identifying early behaviors and understanding the consequences brain development provide a path for cognitive neuroscience to inform early intervention. Brain–behavior relationships help understand the typical interaction between psychological and biological processes, and the missing biological pieces in atypical development.

The development of spoken language is resilient and also remarkably similar across languages. Recently, a brain imaging study of four different languages (Spanish, English, Hebrew, and Chinese) showed the universality of the language network in the brain.[9] In all languages, the traditional left frontal–temporal network of the brain was activated for listening comprehension, and it was remarkably overlapping. Such findings provide the basis for future models of prediction of language outcome across cultures. There is invariance in structures that develop for speech comprehension despite the different characteristics of sound and structure of spoken languages. The study also showed a common brain signature for reading in the four languages. Despite the significant differences in writing systems (alphabetic and ideographic, for example), the brain signature for reading is largely similar in the four languages; it is also largely constrained by the speech processing system.[9] Earlier studies showed how the centers that adapt for processing print are constrained by the centers hardwired for spoken language (of course, with the exception of visual centers). Once children learn to read, the centers for processing print are grafted onto a left-lateralized network of language areas hardwired for spoken language. This has been shown for English and for Portuguese, for example.[29,30] Fig. 1 demonstrates the overlap in centers involved for speech and print processing for Portuguese (adapted from Buchweitz et al.).[29] Similar centers were identified in the study of four different languages.

Figure 1 The left frontoparietal network of regions for listening and reading (red: listening; green: reading; white: overlap).

Based on the notion that there is a hardwired language circuitry, and that instruction-dependent reading development is constrained by this circuitry, it is possible to reframe this information in the light of prediction of language outcome. By knowing what underlying biological centers have to develop and the adaptations that follow from learning, it is possible to establish a neural account of spoken language and reading development within the framework of prediction. Some of the neural adaptations to reading are discussed below.

Reading development: a fragile process and its associated adaptations in the brain

Learning to read is instruction-dependent, and it systematically changes the human visual circuitry and the way language sounds are processed. Studies show lasting effects on the processing of auditory word-form. Illiterate adults are incapable of deleting or adding sounds from pseudowords (words that do not exist, but are made up of regular consonant and vowel structures).[37] The systematic changes in brain function that take place are likely candidates for neuromarkers of typical and poor reading development. One such change has been identified in illiterate adults: they do not process made-up words using the same brain centers literate adults do[38] and they have difficulty repeating back made-up words and making word associations based on sound.[39] These difficulties follow from not having learned the visual boundaries of words and the corresponding boundaries in sound.

One of the consequences of learning to read is that the human ability to recognize mirror images slows down (contrary to natural human mirror-imaging abilities, learning to read means ''unlearning'' to mirror ''b'' and ''d,'' for example).[40] When one learns to read, a specific center in the occipitotemporal region reprograms itself; it adapts from its original function of processing faces and objects to specializing in the identification of the visual form of words.[41–43] The activation of the occipitotemporal region in association with the presentation of letters and words is a marker of reading development. The more a child learns to read, the more the occipitotemporal region activates in response to visual processing of words. The specific region that adapts to the recognition of letters and words has been coined the visual word form area (VWFA).[43–45] In illiterate adults, the VWFA does not light up when words are presented visually. It does not activate for visual linguistic stimuli differently than it activates for nonlinguistic visual stimuli. Also, the activation of the region is modulated by how late one learns to read. The VWFA activates significantly more in people who have learned to read as children than in those who learned to read only as adults. The different levels of activation of the VWFA correlate with reading fluency.[44] The activation of the VWFA in early years is predictive of reading outcomes and is a marker of fluent reading.[6,42,45]

Pathways from the human visual circuitry to other centers in the brain develop with reading. Two pathways, or routes, develop in parallel: the dorsal, or phonological route and the ventral, or lexical route. The left temporoparietal region is part of the dorsal route of the brain that develops with reading. The dorsal pathway includes

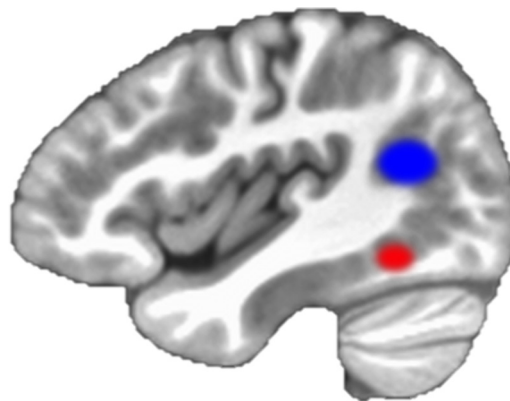**Table 1** Brain regions associated with reading development.

Region (left hemisphere)	Brain–behavior relationship	Reference
Occipitotemporal[a]	Recognition of letters; adaptation of the visual circuit to reading.	6,9,40,43,45
Temporoparietal	Development of the phonological route (letter-sound associations)	33,44,47,48

[a] Also known as the visual word form area.

left temporoparietal and left inferior frontal regions. The development of the dorsal pathway is associated with learning print and sound associations.[43] Brain imaging has also revealed that activation of the dorsal pathway develops with age[46]; and that the temporoparietal component of the pathway is hypoactive in dyslexic children.[33,47] It is a brain circuitry that develops with learning to read and fails to develop when there are obstacles to reading fluently. The ventral pathway, in turn, develops with reader fluency and with the learning of irregularities of language (such as one vowel having more than one possible sound).

Brain imaging has produced evidence about markers of reading development, and the importance of early instruction for reading. The question is no longer whether brain imaging has the potential to inform practices and generate predictions. The scientific question, it seems, lies in producing more generalizable evidence and replicating studies with larger populations; the political and ethical issues should follow. One promise for prediction lies in the interaction between brain imaging and machine learning algorithms, which is briefly addressed below. Table 1 shows studies that identified neural markers in association with reading development. Fig. 2 shows a rendering of the two centers discussed above, the occipitotemporal and the temporoparietal regions.

In sum, cognitive neuroscience and brain imaging have produced evidence of brain and behavior relationships that

Figure 2 The visual word form area (red circle) and the temporoparietal region (blue circle): brain markers of reading development.

inform the basis of typical and atypical language development. The challenge is how to make the evidence more reliable to the point of informing educational and health policies. The application of machine learning algorithms to brain imaging data in combination with large-scale brain imaging studies is an exciting possibility to produce more evidence-based educational policies.

A mandate for the neurosciences: prediction of health and education-related outcomes

The application of machine learning algorithms to identify patterns in human activity is changing the way human behavior can be investigated and predicted. These algorithms identify patterns in instant messaging, traffic, and health-related Internet queries (*i.e.*, for the word ''influenza'') that may raise red flags for possible epidemics.[48] The recent advances in the use of machine learning algorithms have made it possible to reliably identify cognitive states and psychiatric disorders using brain imaging data.[49–53]

Machine learning algorithms can unveil patterns of brain activity that can be tested on new sets of brain imaging data for their generalizability; patterns associated with human emotions or with clinical populations have been tested on entirely new brain imaging data sets.[50,54] Machine learning has been applied to identify autism from the brain data alone,[50] to identify cognitive states,[51,54,49] to identify brain patterns for emotions,[52] and to identify brain patterns that identify when new concepts are learned.[55] The issue that emerges is how to support more use of machine learning algorithms and knowledge in the neurosciences. Identification of early markers of health and cognition-related outcomes holds promise for a positive effect in quality of life and in return-on-investment of public funding for science and healthcare. These algorithms can be used to test whether the neural markers of language and reading development extrapolate to larger populations, and predict language outcomes. Brain imaging evidence is accumulating and artificial intelligence algorithms continue to improve. Education and healthcare should benefit from these advances.

Conflicts of interest

The author declares no conflicts of interest.

References

1. Rosen BR, Savoy RL. fMRI at 20: has it changed the world? Neuroimage. 2012;62:1316–24.
2. Price CJ. The anatomy of language: a review of 100 fMRI studies published in 2009. Ann NY Acad Sci. 2010;1191:62–88.
3. Cabeza R, Nyberg L. Imaging cognition II: an empirical review of 275 PET and fMRI studies. J Cogn Neurosci. 2000;12:1–47.
4. Gabrieli JD. Dyslexia: a new synergy between education and cognitive neuroscience. Science. 2009;325:280–3.
5. Pugh KR, Frost SJ, Rothman DL, Hoeft F, Del Tufo SN, Mason GF, et al. Glutamate and choline levels predict individual differences in reading ability in emergent readers. J Neurosci. 2014;34:4082–9.
6. Shaywitz BA, Shaywitz SE, Blachman BA, Pugh KR, Fulbright RK, Skudlarski P, et al. Development of left occipitotemporal systems for skilled reading in children after a phonologically-based intervention. Biol Psychiatry. 2004;55:926–33.
7. Hoeft F, McCandliss BD, Black JM, Gantman A, Zakerani N, Hulme C, et al. Neural systems predicting long-term outcome in dyslexia. Proc Natl Acad Sci U S A. 2011;108:361–6.
8. Deniz Can D, Richards T, Kuhl PK. Early gray-matter and white-matter concentration in infancy predict later language skills: a whole brain voxel-based morphometry study. Brain Lang. 2013;124:34–44.
9. Rueckl JG, Paz-Alonso PM, Molfese PJ, Kuo WJ, Bick A, Frost SJ, et al. Universal brain signature of proficient reading: evidence from four contrasting languages. Proc Natl Acad Sci U S A. 2015;112:15510–5.
10. Shaywitz BA, Shaywitz SE, Pugh KR, Mencl WE, Fulbright RK, Skudlarski P, et al. Disruption of posterior brain systems for reading in children with developmental dyslexia. Biol Psychiatry. 2002;52:101–10.
11. Devlin JT, Jamison HL, Gonnerman LM, Matthews PM. The role of the posterior fusiform gyrus in reading. J Cogn Neurosci. 2006;18:911–22.
12. Gabrieli JD, Ghosh SS, Whitfield-Gabrieli S. Prediction as a humanitarian and pragmatic contribution from human cognitive neuroscience. Neuron. 2015;85:11–26.
13. Hoeft F, Ueno T, Reiss AL, Meyler A, Whitfield-Gabrieli S, Glover GH, et al. Prediction of children's reading skills using behavioral, functional, and structural neuroimaging measures. Behav Neurosci. 2007;121:602–13.
14. Bandettini PA. Twenty years of functional MRI: the science and the stories. Neuroimage. 2012;62:575–88.
15. Huettel SA, Song AW, McCarthy G. Functional magnetic resonance imaging. Sunderland, MA: Sinauer Associates; 2004.
16. Logothetis NK, Pauls J, Augath M, Trinath T, Oeltermann A. Neurophysiological investigation of the basis of the fMRI signal. Nature. 2001;412:150–7.
17. Logothetis NK. What we can do and what we cannot do with fMRI. Nature. 2008;453:869–78.
18. Beaulieu C, Plewes C, Paulson LA, Roy D, Snook L, Concha L, et al. Imaging brain connectivity in children with diverse reading ability. Neuroimage. 2005;25:1266–71.
19. Klingberg T, Hedehus M, Temple E, Salz T, Gabrieli JD, Moseley ME, et al. Microstructure of temporo-parietal white matter as a basis for reading ability: evidence from diffusion tensor magnetic resonance imaging. Neuron. 2000;25:493–500.
20. Myers CA, Vandermosten M, Farris EA, Hancock R, Gimenez P, Black JM, et al. White matter morphometric changes uniquely predict children's reading acquisition. Psychol Sci. 2014;25:1870–83.
21. Keller TA, Just MA. Altering cortical connectivity: remediation-induced changes in the white matter of poor readers. Neuron. 2009;64:624–31.
22. Molfese DL. Predicting dyslexia at 8 years of age using neonatal brain responses. Brain Lang. 2000;72:238–45.
23. Mencl WE, Frost S, Pugh KR. Tools for multimodal imaging. In: McCardle P, Pugh KR, editors. How children learn to read: current issues and new directions in the integration of cognition, neurobiology and genetics of reading and dyslexia. New York: Psychology Press; 2009. p. 87–98.
24. National Research Council (US) and Institute of Medicine (US) Committee on Integrating the Science of Early Childhood Development. In: Shonkoff JP, Phillips DA, editors. From neurons to neighborhoods: the science of early childhood development. Washington, DC: National Academies Press; 2000.
25. Beddington J, Cooper CL, Field J, Goswami U, Huppert FA, Jenkins R, et al. The mental wealth of nations. Nature. 2008;455:1057–60.
26. Hoff E. The specificity of environmental influence: socioeconomic status affects early vocabulary development via maternal speech. Child Dev. 2003;74:1368–78.

27. Hoff E, Tian C. Socioeconomic status and cultural influences on language. J Commun Disord. 2005;38:271–8.

28. Noble KG, Houston SM, Brito NH, Bartsch H, Kan E, Kuperman JM, et al. Family income, parental education and brain structure in children and adolescents. Nat Neurosci. 2015;18:773–8.

29. Buchweitz A, Mason RA, Tomitch LM, Just MA. Brain activation for reading and listening comprehension: an fMRI study of modality effects and individual differences in language comprehension. Psychol Neurosci. 2009;2:111–23.

30. Michael EB, Keller TA, Carpenter PA, Just MA. fMRI investigation of sentence comprehension by eye and by ear: modality fingerprints on cognitive processes. Hum Brain Mapp. 2001;13:239–52.

31. Shaywitz S. Overcoming dyslexia: a new and complete science-based program for reading problems at any level. New York: Vintage Books; 2008.

32. Shaywitz SE, Shaywitz BA. Paying attention to reading: the neurobiology of reading and dyslexia. Dev Psychopathol. 2008;20:1329–49.

33. Kovelman I, Norton ES, Christodoulou JA, Gaab N, Lieberman DA, Triantafyllou C, et al. Brain basis of phonological awareness for spoken language in children and its disruption in dyslexia. Cereb Cortex. 2012;22:754–64.

34. Preston JL, Frost SJ, Mencl WE, Fulbright RK, Landi N, Grigorenko E, et al. Early and late talkers: school-age language, literacy and neurolinguistic differences. Brain. 2010;133:2185–95.

35. Ullman MT, Pierpont EI. Specific language impairment is not specific to language: the procedural deficit hypothesis. Cortex. 2005;41:399–433.

36. Ullman MT, Corkin S, Coppola M, Hickok G, Growdon JH, Koroshetz WJ, et al. A neural dissociation within language: evidence that the mental dictionary is part of declarative memory, and that grammatical rules are processed by the procedural system. J Cogn Neurosci. 1997;9:266–76.

37. Morais J, Cary L, Alegria J, Bertelson P. Does awareness of speech as a sequence of phones arise spontaneously? Cognition. 1979;7:323–31.

38. Castro-Caldas A, Petersson KM, Reis A, Stone-Elander S, Ingvar M. The illiterate brain. Learning to read and write during childhood influences the functional organization of the adult brain. Brain. 1998;121:1053–63.

39. Reis A, Castro-Caldas A. Illiteracy: a cause for biased cognitive development. J Int Neuropsychol Soc. 1997;3:444–50.

40. Pegado F, Nakamura K, Braga LW, Ventura P, Nunes Filho G, Pallier C, et al. Literacy breaks mirror invariance for visual stimuli: a behavioral study with adult illiterates. J Exp Psychol Gen. 2014;143:887–94.

41. Cohen L, Dehaene S, Naccache L, Lehéricy S, Dehaene-Lambertz G, Hénaff MA, et al. The visual word form area: spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. Brain. 2000;123:291–307.

42. Dehaene S, Cohen L. The unique role of the visual word form area in reading. Trends Cogn Sci. 2011;15:254–62.

43. Dehaene S. Reading in the brain: the new science of how we read. New York: Penguin Books; 2009.

44. Dehaene S, Pegado F, Braga LW, Ventura P, Nunes Filho G, Jobert A, et al. How learning to read changes the cortical networks for vision and language. Science. 2010;330:1359–64.

45. Cohen L, Lehéricy S, Chochon F, Lemer C, Rivaud S, Dehaene S. Language-specific tuning of visual cortex? Functional properties of the Visual Word Form Area. Brain. 2002;125:1054–69.

46. Meyler A, Keller TA, Cherkassky VL, Lee D, Hoeft F, Whitfield-Gabrieli S, et al. Brain activation during sentence comprehension among good and poor readers. Cereb Cortex. 2007;17:2780–7.

47. Maurer U, Schulz E, Brem S, der Mark SV, Bucher K, Martin E, et al. The development of print tuning in children with dyslexia: evidence from longitudinal ERP data supported by fMRI. Neuroimage. 2011;57:714–22.

48. Mitchell TM. Computer science. Mining our reality. Science. 2009;326:1644–5.

49. Buchweitz A, Shinkareva SV, Mason RA, Mitchell TM, Just MA. Identifying bilingual semantic neural representations across languages. Brain Lang. 2012;120:282–9.

50. Just MA, Cherkassky VL, Buchweitz A, Keller TA, Mitchell TM. Identifying autism from neural representations of social interactions: neurocognitive markers of autism. PLOS ONE. 2014;9:e113879.

51. Shinkareva SV, Mason RA, Malave VL, Wang W, Mitchell TM, Just MA. Using FMRI brain activation to identify cognitive states associated with perception of tools and dwellings. PLOS ONE. 2008;3:e1394.

52. Kassam KS, Markey AR, Cherkassky VL, Loewenstein G, Just MA. Identifying emotions on the basis of neural activation. PLoS ONE. 2013;8:e66032.

53. Chang KM, Mitchell T, Just MA. Quantitative modeling of the neural representation of objects: how semantic feature norms can account for fMRI activation. Neuroimage. 2011;56:716–27.

54. Mitchell TM, Shinkareva SV, Carlson A, Chang KM, Malave VL, Mason RA, et al. Predicting human brain activity associated with the meanings of nouns. Science. 2008;320:1191–5.

55. Bauer AJ, Just MA. Monitoring the growth of the neural representations of new animal concepts. Hum Brain Mapp. 2015;36:3213–26.