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阅读能力个体差异的神经机制研究进展

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提要　阅读是人脑的高级功能之一，也是现代社会人们生活中不可缺少的一部分。由于文字短暂的进化史，人类缺乏专门的基因和神经模块负责文字加工，阅读需要经过多年的专门学习和系统训练，这一过程也带来了阅读能力的显著个体差异。随着功能影像技术的发展，研究者在阅读的认知神经科学领域取得了较大进展，并逐步揭示了阅读能力的个体差异，特别是正常群体内部个体差异的认知和神经机制。本文首先概述阅读所涉及的基本认知过程及神经机制，然后从脑功能和脑结构方面，综述近年来对阅读能力个体差异的认知神经机制研究的主要发现，并进一步讨论建立个体神经水平差异与阅读能力之间因果关系的几种重要的研究方法及有关成果。文章最后对阅读能力个体差异的未来研究方向提出几点建议。
关键词　阅读能力　个体差异　神经机制　因果关系

The Neural Substrates Underlying the Individual Differences of Reading Abilities

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Abstract　Reading is an indispensible part of human life in the modern era. Due to the relatively short history of written languages in human evolution, it is generally believed that the human is unlikely to have developed specialized genes or neural circuitries to process written languages. Probably due to this reason, fluent reading involves years´ of formal education and training, and there are significant individual differences in reading abilities. With the development of noninvasive functional imaging techniques in the last two decades, researchers have made major progresses in understanding the neural substrates of individual differences in reading abilities.

The present paper aims at reviewing the cognitive process and neural mechanisms of reading as well as some of the exciting advances in understanding the neural basis of individual differences. Existing studies have revealed at least three brain regions involved in reading, including the temporooccipital cortex, the temporoparietal cortex and the inferior frontal cortex. Consistent with the dual-route model suggested by the behavioral, neuropsychological, and computational studies, the left supramarginal gyrus, posterior superior temporal gyrus, and dorsal inferior frontal gyrus are mainly involved in assembled phonology, i.e., the indirect route, which transforms visual words into phonology through grapheme-to-phoneme correspondences (GPC). In contrast, the ventral part of the lateral temporal cortex and the inferior frontal gyrus are mainly involved in the addressed phonology, i. e., the direct route, which achieves phonological access via the direct associations between the visual forms of words and their sounds.

Furthermore, existing studies have shown that the many neural measures are associated with individual differences in reading abilities, including brain activity levels, gray matter volume, white matter integrity and functional connectivity among multiple brain regions, which is modulated by the characteristics of different writing systems. In particular, increased activity in left-hemisphere middle temporal and inferior frontal gyri and decreased activity in right inferotemporal cortical areas are associated with better reading abilities. Whereas the cortical thickness of the temporoparietal area is positively correlated with the reading of irregular words, the gray matter volume in the left middle frontal gyrus is correlated with Chinese word reading. In contrast, the cortical thickness in the left mid-fusiform gyrus was positively correlated with performance on reading abilities of both Chinese characters and English words, suggesting its common role in the reading of different writing systems. Using diffusion tensor imaging (DTI) to measure the white matter integrity indexed by fractional anisotropy (FA), it has been shown that the FA of left temporoparietal area, left frontal lobe and corpus callosum was associated with reading ability. Functional connectivity studies further suggested that the connection strength between the left temporoparietal region and the Broca area is positively correlated with reading ability. Finally, resting-state functional connectivity (RSFC) within the reading network has also been linked to reading abilities in native language (L1) and second language (L2).

Keywords reading ability, individual differences, neural mechanisms, causal relationship

1. 引言

在当今信息驱动的社会，阅读对于个体的生存和发展起着至关重要的作用。同时，在全球化的今天，掌握一种或多种外语也越来越普遍。语言是人类特有的技能，但语言能力的不同方面具有不同的进化和文化起源。例如，虽然口语是生物进化的结果，而阅读和书写却是近五千年来才产生的文化发明。相对于人类漫长的进化史，这个短暂的时间不足以让人类进化出特定的基因或者先天的神经网络负责文字加工(McCandliss，et al. 2003) 。相反，阅读能力的获得和发展是一个渐进累积的过程，即在一定的遗传基础上，通过早期家庭的自发式学习，以及后期的系统教育和训练逐步掌握，最后在成人期进一步发展和完善。基于此，Dehaene 和 Cohen(2007) 的神经元再利用假说(neuronal recycling hypothesis) 认为，文化的获得(如阅读) 需要找到一系列负责该功能的神经回路(如视觉加工、物体识别) ，并在此基础上发展新的用途。人脑需要在多年的系统学习中，重新利用并塑造该网络的结构和功能，来实现高效和自动化的阅读加工。

虽然阅读能力的获得和发展在各个文化和群体中存在相似的规律，但不同个体之间的阅读能力差异却是广泛存在的。例如，有人可以快速有效地学会阅读多种语言，但是有人却存在阅读困难(如阅读障碍) ，尽管他们具有正常的智

力、完整的神经结构以及相等的学习机会。此外，尽管大部分人能够流利地阅读母语，但在学习第二语言时却存在较大的困难。因此，从遗传、行为、认知以及脑结构和脑功能等多个角度揭示阅读能力的个体差异，具有重要的理论和实践意义，并得到了学术界的广泛关注。

阅读能力的个体差异包含阅读障碍和正常人之间的差异，以及正常人群内部的差异。对于前一个问题已经有很多文章进行了综述(Pugh，et al. 2000a; Shaywitz and Shaywitz 2003，2005; Vellutino，et al. 2004; Pugh 2006; Vandermosten，et al. 2012b) 。本文重点探讨正常人群内部阅读能力个体差异的神经机制。文章首先概述阅读的认知神经机制，接着从神经层面探讨阅读能力个体差异的机制，并进一步探讨建立个体神经水平差异与阅读能力之间因果关系的研究方法，最后对未来有关研究做出简要的展望。

2. 阅读的认知神经机制概述

阅读加工包含多个认知成分和加工过程。在神经机制上，阅读也是由一个广泛的神经网络来支持。在本节中，我们将首先简述阅读的认知过程，然后介绍与阅读有关的脑区以及阅读中语音通达的神经双通路机制。

早在上个世纪，认知心理学家们就阅读所包含的各种认知成分和过程提出了很多模型，包括模块化的认知加工模型和联结主义模型(connectionist model，Seidenberg and McClelland 1989; Price and Friston 1997; Price 2000) 。其中，Coltheart 等(1993) 提出的"双通路模型"得到了普遍的认可，并对阅读的神经机制研究有很大的影响。该模型认为，阅读者首先从"视觉特征分析"开始。经过视觉分析，识别词中的各个字母，视觉文字被转换成抽象的形式(letter identification) ，这种抽象的形式独立于其位置、大小、颜色等外部信息。视觉分析之后，词开始进入不同的加工过程。阅读者认识和熟悉的词进入"视觉输入词典"，如果与词典中的某个表征一致，该词就被识别了。之后词进入语义系统，与阅读者已有的知识发生联系并被理解。接着词进入"语音输出词典"进行语音提取，阅读者随后产出言语。这个过程就是直接的语音提取通路。对于不熟悉、不认识的词或者无意义的假词，阅读者在视觉识别之后利用形音转换规则，通过拼读词的语音进行言语产出。这就是间接的拼读通路。Coltheart 等(2001) 修订版的双通路模型认为，语音提取通路和拼读通路并不是完全分离的。两个过程会同时参与，甚至说是相互竞争。同时，词汇阅读使用哪条通路并不是不变的，随着阅读经验的增加、词汇熟悉性的增强，会越来越多地使用直接的语音提取通路，而拼读通路的作用会慢慢减弱。

采用功能磁共振技术(functional magnetic resonance imaging，fMRI) ，以阅读障碍和正常群体为被试，研究者发现了阅读中最重要的三个脑区(颞枕皮层、

颞顶皮层和额下皮层）。其中，位于颞枕区域的左侧梭状回在词汇的视觉字形加工中具有非常重要的作用（Cohen，et al. 2000）。元分析结果发现它在不同文字系统中的作用是非常相似的（Bolger，et al. 2005），除了母语加工，也参与第二语言（Tan，et al. 2011）以及新语言（Xue，et al. 2006a，2006b）的加工。位于左脑外侧裂的颞顶皮层包括三个子区域：颞上回后部、缘上回和角回。对于颞上回后部的功能，研究一致认为其是负责语音加工的区域（Price 2000; Vigneau，et al. 2006）。对于缘上回和角回的作用，目前研究还没有得到一致的结论。有研究认为缘上回和角回与语义加工有关（Price 2000; Vigneau，et al. 2006），但是还有研究报告缘上回是阅读中跨通道（形音）转换的区域（Booth，et al. 2002，2004），角回负责语音通达过程，不涉及语义加工（Shaywitz，et al. 1998; Pugh，et al. 2000a; Shaywitz，et al. 2002; Shaywitz and Shaywitz 2003，2005; Hoeft，et al. 2007）。进一步白质连接的研究发现，缘上回和角回所在通路上的分离导致两者在功能上的差异：缘上回主要连接语音加工的额下皮层后部，而角回则连接语义加工的区域（Catani，et al. 2002; Catani，et al. 2005）。最后，额下回也分为三个子区域：额下回眶部、三角部和盖部。研究者通过比较一系列只有语音或语义的任务，发现背侧后部的额下回盖部负责语音加工，而背侧前部的三角部和腹侧的眶部负责语义加工（Poldrack，et al. 1999）。这一发现后来得到了大量实证研究和元分析研究的证实（Demb，et al. 1995; Warburton，et al. 1996; Zatorre，et al. 1996; Jessen，et al. 1999; Paulesu，et al. 2000; Adams and Janata 2002; Booth，et al. 2002; Gurd，et al. 2002; Binder，et al. 2003; Bright，et al. 2004; Ronnberg，et al. 2004）。

与阅读的双通路模型对应，拼读和语音提取也涉及两种不同的神经通路（Jobard，et al. 2003），拼读通路主要由颞上回、缘上回和前额叶鳃盖部负责；语音提取通路主要由颞下回、颞中回后部和额下回的三角区域负责，这些区域在语义加工中扮演着重要的角色。这些结果主要来自于真词和假词的阅读比较（Herbster，et al. 1997; Brunswick，et al. 1999; Fiez，et al. 1999; Hagoort，et al. 1999; Fiebach，et al. 2002; Simos，et al. 2002; Mechelli，Gorno-Tempini，et al. 2003; Mechelli，Crinton，et al. 2005; Nosarti，et al. 2010），发音不规则词汇和发音规则词汇的阅读比较（Fiez，et al. 1999; Mechelli，et al. 2005; Nosarti，et al. 2010），汉字和汉语拼音的阅读比较（Chen，et al. 2002; Fu，et al. 2002）以及词汇/语义判断和语音判断任务比较（Rumsey，et al. 1997; Poldrack，et al. 1999; Burton，et al. 2003; Devlin，et al. 2003; McDermott，et al. 2003; Kuo，et al. 2004）。以上研究多使用自然语言为材料，虽然具有

较强的生态学效度，但无法完全控制材料之间在视觉复杂性、材料的熟悉性、语音或语义等方面的差异。为了克服这些困难，Mei 等(2014) 采用人工语言训练的范式，严格控制拼读(形音对应有规则) 和语音提取(形音对应规则被打乱) 两组实验材料的视觉复杂性、语音、熟悉性及学习经验等方面的差异，以期能够更清晰地揭示两条阅读通路的神经机制。结果发现，语音提取在前扣带皮层、后扣带皮层、右眶额皮层、角回以及颞中回有较强的激活，而拼读在左侧中央前回/额下回和缘上回有较强的激活。由此证实了阅读的神经双通路模型。有趣的是，研究还发现，随着对材料熟悉性的增加，拼读组材料在神经通路上从拼读通路向语音提取通路转换，从而在神经层面支持了修订版的双通路模型(Coltheart，et al. 2001; Binder，et al. 2005; Maloney，et al. 2009) 。

3. 阅读能力个体差异的神经机制

研究者经常发现，无论在阅读的行为表现，如阅读速度和正确性，还是在阅读的神经机制上均存在不可忽略的个体差异(Xiong，et al. 1998) ，这种差异在学习和加工新语言的过程中尤为明显(Dehaene，et al.，1997) 。这个领域一个重要的问题是，个体差异在阅读过程中的神经机制是怎样的? 近年来磁共振技术的进步为探讨阅读能力个体差异提供了多种手段。利用这些手段，研究者们不仅能探讨传统任务状态下脑激活强度与阅读能力个体差异的关系，还能开始探讨脑灰质结构、脑白质结构与阅读能力个体差异的关系，以及多个脑区(皮层) 功能连接与阅读能力个体差异的关系。本节将对各种脑成像技术下取得的脑-阅读能力关系的研究进行讨论。

3.1 大脑功能层面的阅读能力个体差异

对于大脑功能与阅读能力个体差异的关系，早期通过对比阅读障碍者与正常人在阅读任务中大脑激活强度差异后发现，与正常人相比，阅读障碍者在阅读时相关脑区(左侧颞顶、颞枕以及额下区域) 存在激活异常(Shaywitz，et al. 1998; Simos，et al. 2000a; Simos，et al. 2000b; McCrory，et al. 2005; Cao，et al. 2006; van der Mark，et al. 2009) 。在正常群体中，研究发现，大脑左侧阅读相关脑区(颞中、额下皮层) 的正激活与阅读能力有关，而右侧颞下皮层的负激活与阅读能力有关(Turkeltaub，et al. 2003) 。另外，采用事件相关电位(event related potential，ERP) 和 fMRI 同时考察视觉词汇识别脑机制的研究发现，ERP 的 N1 波幅(被认为是特异于字形加工的成分) 和左侧梭状回的活动与被试的阅读成绩存在正相关，即被试的阅读成绩越好，N1 波幅越大，其在左侧梭状回的激活也越强(Brem，et al. 2006) 。其他研究也发现了相似的结果(Turkeltaub，et al. 2003; Schlaggar and McCandliss 2007; Bruno，et al. 2008) 。

采用脑功能成像的方法揭示阅读能力的个体差异具有非常明显的优势，可以直接反映阅读加工过程。但采用任务态脑成像的一个重大挑战是，大脑激活水平的差异可能仅仅反映了不同认知过程的差异，而不是大脑功能的差异。由于个体阅读能力的差异，相同的阅读任务可能带来任务难度的差异。一方面，如果难度太大，有些个体无法完成该任务，就会导致个体放弃加工或者使用猜测的方式，从而导致不同认知过程的参与和激活模式的差异；为了减少这个过程对激活模式的影响，在分析中一般需要排除错误的材料。另一方面，任务难度的差异还反映在加工时间以及大脑参与时间的差异。为了克服这个影响，往往需要把反应时作为协变量排除。但这些统计的方法并不能应对反应时和大脑活动的非线性关系。更重要的是，如果个体采用不同的认知加工策略或者一些补偿机制，情况就更加复杂。为此，研究者往往采用非常简单的阅读任务来减少任务表现对大脑激活的影响。近年来，研究者开始考察非任务状态下大脑结构和静息态功能活动的差异与阅读能力之间的关系。

3.2 脑灰质结构层面的阅读能力个体差异

同任务态相比，采用非任务状态下的脑结构数据考察阅读能力个体差异的神经机制，具有独特的优势。例如，测量数据不受任务的影响，可以采用自动化的分析技术，从而方便进行大样本的研究，并提高研究的效率和结果的可靠性。对于脑结构的研究通常考察灰质和白质的结构。其中，灰质是中枢神经系统中大量神经元聚集的部位，能够对信息进行深入处理；白质由神经元的轴突组成，本身不具有处理信息的功能，但是能在不同灰质之间或者灰质与外周器官之间传递信息，协调脑区之间的正常运作。对于大脑结构灰质的研究通常以皮层厚度和灰质密度(或体积)为测量指标，采用的方法包括基于体素的形态学测量(voxel-based morphometry，VBM)方法(Ashburner and Friston 2000)及基于表面的(surface-based)分析方法(Dale，et al. 1999；Fischl，et al. 1999)等。

在阅读能力与大脑皮层厚度的关系上，研究发现负责形音转换区域(如颞顶区域)的皮层厚度与不规则词汇的阅读能力呈正相关(Blackmon，et al. 2010)，而中文阅读和书写相关脑区(如左侧额中回)的灰质体积与中文的阅读能力有关(Siok，et al. 2008)。另有研究发现左侧梭状回中部的皮层厚度不仅与母语(表义文字)的阅读能力有关，也与第二语言(表音文字)的阅读成绩呈正相关(Zhang，et al. 2013a)，说明大脑灰质结构在不同语言的阅读能力中都起到重要作用。阅读能力包括语音解码和文本理解两个基本过程，研究发现大学生被试的语音解码能力与颞顶区域皮层厚度的左侧化程度呈正相关，而文本理解能力与右侧额叶的皮层厚度呈正相关(Welcome，et al. 2011)。

上述研究主要采用单个阅读任务来定义个体的阅读能力。但阅读是一个复

杂的过程，包含多个不同的成分，单个任务往往无法涵盖所有成分，也无法对各个成分进行准确区分。He 等(2013)以 416 名大学生为被试，采用 7 个阅读任务系统，分离出阅读能力的三个成分：语音解码、形音连接和阅读速度。他们进一步采用多元模式分析(multivariate pattern analysis，MVPA)的方法探讨了其中 253 名被试的大脑灰质体积和阅读能力各个子成分之间的关系。结果发现，左上顶叶延伸到缘上回的灰质体积与语音解码有关，海马和小脑的灰质体积能够预测形音连接的成绩，大脑枕叶、颞叶、顶叶以及额叶皮层的灰质体积与阅读速度存在相关；同时，语音解码和形音连接独立于一般的认知能力，如智力、记忆和加工速度，而阅读速度和智力以及加工速度存在一定相关。

3.3 脑白质结构层面的阅读能力个体差异

阅读的完成需要大脑多个区域的协同活动，而白质纤维的连接在其中起到重要作用。研究者主要采用弥散张量成像(diffusion tensor imagine，DTI)来考察白质的特性。目前有许多量化的参数来描述白质的弥散张量，其中各向异性(fractional anisotropy，FA)能很好地反映白质纤维束连接的有效性(FA 值越大，白质纤维连接越有效)，从而在认知神经科学研究中得到广泛使用。利用 DTI 中的纤维追踪技术，研究者找到了连接语言重要脑区的多条白质纤维，包括连接枕叶和颞叶的下纵束(inferior longitudinal fasciculus，ILF)、连接枕叶和额叶的下额枕束(inferior fronto-occipital fasciculus，IFOF)、连接额叶与颞叶、顶叶和枕叶的上纵束(superior longitudinal fasciculus，SLF)等。

Klingberg 等(2000)第一次考察了 FA 与阅读能力的关系，结果发现阅读能力强的被试双侧颞顶区域的 FA 值更高。后来许多研究者多次验证了左侧颞顶区域的白质纤维 FA 值与阅读能力的关系(Beaulieu，et al. 2005; Deutsch，et al. 2005; Niogi and McCandliss 2006; Steinbrink，et al.，2008; Carter，et al. 2009; Odegard，et al. 2009; Rimrodt，et al. 2010; Lebel，et al. 2013; Zhang，et al. 2014)。除了颞顶区域，左侧额叶(Deutsch，et al. 2005; Richards，et al. 2008; Steinbrink，et al. 2008; Carter，et al. 2009; Rimrodt，et al. 2010)以及胼胝体(Dougherty，et al. 2007; Frey，et al. 2008; Odegard，et al. 2009)的 FA 值都与阅读能力相关。还有研究发现下额枕束和下纵束的 FA 值与阅读能力有关(Vandermosten，et al. 2012a)。

目前为止，有关白质纤维束的连接与阅读能力关系的证据大都来自于小样本阅读障碍者与正常人的比较。一项针对正常群体的大样本研究发现，大脑双侧区域尤其是额叶、顶叶以及颞叶之间连接的 FA 值与阅读能力呈正相关(Lebel，et al. 2013)。还有两项研究比较了表音文字和表义文字的阅读能力与大脑白质连接的关系。有研究在同一批被试身上比较了汉英双语者的阅读能

力，结果发现左侧内囊前肢的弥散值与中文阅读能力有关，双侧放射冠的弥散值与英语阅读能力有关(Qiu，et al. 2008)。另有研究比较以中文和英文为母语的两组被试后发现，母语阅读能力(无论中文还是英文)都与左侧阅读有关脑区的FA值有关，如与语音加工有关的放射冠、胼胝体及上纵束，与语义加工有关的腹侧钩束、外囊及下额枕束；但位于上纵束中左侧颞叶部分的FA值对英文阅读能力的贡献大于中文，提示上纵束与表音文字的形音转换规则有关(Zhang，et al. 2014)。

3.4 脑功能连接层面的阅读能力个体差异

除了大脑的白质纤维连接，大脑的功能连接强度也是阅读能力的有效神经指标。有多个指标可以考察大脑多个脑区协同活动的情况，包括任务状态下的功能连接(不带方向性)、有效连接(带方向性)，以及非任务状态下的静息态功能连接等。其中，种子点方法(seed methods；Biswal，et al. 1995)、聚类(Cordes，et al. 2002)、独立成分分析(independent component analysis，ICA；Greicius，et al. 2004)、主成分分析(principle component analysis，PCA；Friston，et al. 1993)是常见的全脑功能连接方法。与功能连接不同的是，有效连接探讨的是一个神经系统对其他神经系统的影响，方法包括结构方程模型(structural equation modeling，SEM；McIntosh and Gonzalez-Lima 1994)、结构因果模型(structural causal modeling，SCM；White and Lu 2010)、动态因果模型(dynamic causal modeling，DCM；Friston，et al. 2003)、格兰杰因果关系(Granger causality，GC；Roebroeck，et al. 2005)等。上述方法也可以考察非任务状态下的静息态功能连接。

早期比较阅读障碍者和正常被试功能连接的研究发现，正常被试阅读过程中，左侧角回与负责视觉分析的颞枕区域的功能连接强度，负责语音和语义加工的威尔尼克区(Wernicke's area)与布洛卡区(Broca's area)的功能连接强度都显著高于阅读障碍者(Horwitz，et al. 1998)。此后的一项研究也证实了阅读障碍者在阅读中角回与其他阅读相关脑区的功能连接减弱(Pugh，et al. 2000b)。在正常人群的阅读中，左侧颞顶角回(BA39)与布洛卡区的连接强度与阅读能力呈正相关(Hampson，et al. 2006)。

近年来，研究者们开始关注静息状态下阅读相关脑区的连接与阅读能力的关系。研究发现，左侧枕下回和顶上小叶、左侧颞下回和顶下小叶、右侧梭状回和顶上小叶的静息态功能连接强度与母语阅读能力呈正相关(Wang，et al. 2012)。另外，儿童和成人阅读能力的静息态网络既相似也存在差异。其中左侧中央前回和其他运动区的静息态功能连接、布洛卡区和威尔尼克区的静息态功能连接与儿童和成人的阅读能力均呈正相关(Koyama，et al. 2011)。在成人

身上，左侧视觉字形区和布洛卡区以及顶下区域的静息态功能连接与阅读能力呈正相关，左侧视觉字形区和默认网络的静息态功能连接与阅读能力呈负相关。但在儿童身上不存在这种关系，说明左侧视觉字形区与其他脑区的静息态功能连接对阅读的贡献是从儿童到成人中逐步发展起来的(Koyama，et al. 2011) 。静息态功能连接不仅与母语阅读能力有关，也与第二语言的阅读有关。其中，视觉分析区域(如双侧梭状回后部、外侧枕叶皮层和右侧顶上小叶) 与语音加工脑区(如中央前回、中央后回和威尔尼克区) 的静息态功能连接越强，被试母语和第二语言的阅读能力越强(Zhang，et al. 2013b) 。

可以看到，利用 fMRI 技术，研究者们发现有多个神经活动指标，包括任务状态下脑激活强度与功能连接，非任务状态下脑灰质结构、白质结构，以及静息态功能连接均与阅读能力相关。这些研究大大加深了我们对阅读能力及其个体差异的认知神经机制的认识。但是上述研究主要是基于相关分析，因此不能为阅读能力的个体差异提供因果解释。由于大脑具有可塑性，这些结果可能反映了大脑先前的结构和功能对阅读能力的制约，也可能反映了不同阅读过程对大脑结构和功能的塑造，以及两者的交互作用。因此，研究者们试图采用基因、追踪和训练研究的方法，以期建立个体神经水平差异与阅读能力之间的因果关系。

4. 建立个体神经水平差异与阅读能力的因果关系

4.1 基因研究

对于阅读能力个体差异的原因，最直接的方法是从遗传和基因的角度(包括行为遗传学和分子遗传学) 进行探讨。对双生子阅读能力的探讨能够揭示不同阅读能力的遗传度，而利用分子遗传学分析技术则可以揭示与阅读能力有关的基因。

行为遗传学大多以双生子群体为被试，这方面的研究能够从遗传和环境两个方面回答阅读能力个体差异的原因。一系列双生子行为遗传学的研究证实了阅读能力受到遗传因素的影响(DeFries，et al. 1987; Gayan and Olson 2003; Harlaar，et al. 2005; Hawke，et al. 2006; Davis，et al. 2008; Byrne，et al. 2009; Friend，et al. 2009) 。一项对 4291 对双生子的追踪研究发现，语言能力在 7 岁、9 岁和 10 岁时都具有稳定的遗传度(57-67%) ，同时语言能力在一定程度上受到环境的影响(10-17%) (Harlaar，et al. 2007) 。阅读能力的各个方面也在不同程度上受到遗传的影响(Bishop，et al. 2006; Petrill，et al. 2006; Chow，et al. 2011) 。例如语音短时记忆的遗传度为 61%，词法形态为 74%，句法为 82%，词汇为 1%(Bishop，et al. 2006) 。

不仅如此，随着分子遗传学分析技术的出现，研究者们开始在分子水平上

探讨阅读能力个体差异的原因。其中，最著名的便是对 FOXP2 基因的研究。研究者通过染色体组型分析首先在一个患有言语障碍的三代家族——KE 家族中确定了基因位点 SPCH1，然后在 KE 家族之外的另一个障碍个体的 SPCH1 上找到了易位的片段，并将其定名为 FOXP2 基因(Lai，et al. 2001)。后来的研究通过关联分析发现，FOXP2 的多态性与儿童言语运动障碍的发展有关，证实了 FOXP2 在词汇和语言形成中的作用(MacDermot，et al. 2003)。此外，一些与阅读困难和阅读障碍有关的候选基因也相继被发现，例如，DYX1C1 (Taipale，et al. 2003)、DCDC2 (Meng，et al. 2005)、KIAA0319 (Cope，et al. 2005)、ROBO1 (Hannula-Jouppi，et al. 2005)。最后，新近发现的一些关于语言障碍的候选基因，如 CNTNAP2、CMIP 和 ATP2C2 等，均被证实与语音短时记忆、语音解码等各种阅读加工成分有密切关系(Vernes，et al. 2008; Newbury，et al. 2009)。从分子遗传学考察正常群体阅读能力的研究并不多，其中一篇研究发现 DYX1C1 基因能够影响正常儿童阅读能力的发展(Zhang，et al. 2012)。

综上，研究者们从行为遗传学和分子遗传学的角度揭示了阅读能力的个体差异的遗传机制。今后还需要采用全基因扫描技术，在大样本正常群体中进一步发现与阅读能力有关的基因，并深入揭示相关基因的作用机制。

4.2 追踪研究

对于阅读能力的行为追踪研究发现，儿童早期的语音意识、快速阅读和语素意识能够预测后期的阅读能力(Lei，et al. 2011; McBride-Chang，et al. 2011; Zhang，et al. 2013c)。有研究发现，相对于行为指标，结合脑的神经指标对阅读能力的预测作用更有效(Hoeft，et al. 2007; Hoeft，et al. 2011)。研究者分别采用学年初的行为测试数据、脑结构和功能成像数据以及行为和脑数据的结合来预测学年末的阅读成绩。结果表明，整合了行为数据和脑成像数据的综合模型，比起只包含行为数据以及只包含脑成像数据的模型，具有更好的预测效度(Hoeft，Ueno，et al. 2007)。Hoeft 等(2011)进一步开展的追踪研究发现，所有初期的行为测量(包括一些常用的标准化测验)，都不能预测2.5年后阅读障碍儿童阅读能力的提高; 而结合 fMRI 与 DTI 的两个脑测量指标的多变量模型，可以正确预测(正确率为 72%)儿童2.5年后的阅读能力的提高; 语音加工中全脑激活的多变量模型对阅读障碍儿童2.5年后阅读能力提高的预测，能够达到 90%以上的正确率。一般对阅读障碍进行确诊要等到三四年级，但利用脑的神经指标可以实现早期预测。Molfese(2000)的研究发现，利用儿童出生时对言语刺激和非言语刺激反应的脑电指标，可以成功预测 8 岁时哪些儿童将成为正常阅读者，哪些儿童阅读能力较差，哪些儿童会有阅读障碍。

此外，对不同年龄段(9–15 岁)儿童的追踪研究发现，在年龄偏小组，与语音编码有关的脑区(如额下回、基底节)的激活越强，6 年后的阅读能力越好；而在年龄偏大组，视觉分析区域(如颞枕梭状回)的激活越强，6 年后的阅读能力越好(McNorgan，et al. 2011)。这些结果说明，在不同的发展阶段，决定阅读能力的神经机制不同。

可以看到追踪研究能够有效地揭示影响阅读能力的重要因素，并实现阅读能力的早期预测，为早期干预提供了可能。但追踪研究需要持续较长时间，也带来了一些困难，包括样本维护和流失，影响因素多而且测量困难，脑功能成像仪器的更新或老化等导致的误差等。为了克服追踪研究的困难，一些研究者采用训练研究的方法探讨了阅读能力的个体差异。

4.3 训练研究

训练研究可以严格控制语言学习的经验和学习方法，并在相对较短的时间内达到较高的熟练性水平。特别是采用人工语言的训练，能够很好地分离学习阅读的不同成分，从而揭示阅读能力不同方面的神经机制。

通过训练被试学习外语音节模式，有研究发现，与训练前相比，训练后学习较好的被试在左侧颞上后部的激活较强，学习较差的被试在右侧颞上后部、右侧额下回、前额叶以及额叶中部区域的激活较强。更重要的是，研究者还发现，训练前两组被试在神经活动上就存在差异，学习较好的被试在颞上回区域有较强的活动(Wong，et al. 2007)，同时音节学习较差的被试在左侧颞横回的灰质体积较小(Wong，et al. 2008)。此外，外语语音训练的研究发现，学习较快的被试在左侧顶叶(Golestani，et al. 2002)、左侧颞横(Golestani，et al. 2007)区域的白质体积较大。

采用人工语言训练的范式，研究者比较了阅读障碍和非阅读障碍者在学习语音和字形之间连接上的差异，发现阅读障碍者对字母组合能力的缺陷导致学习能力较差(Aravena，et al. 2013)。在正常群体方面，Xue 等(2006a)考察了在学习新的人工语言之前，被试阅读新语言的大脑激活与阅读能力的关系。结果发现，学习前阅读新语言时大脑梭状回左侧化程度越高的被试，新语言的字形学习成绩越好。另外，以往研究已经表明阅读中大脑活动的一侧化存在性别差异，男性主要表现出左侧化，而女性表现出双侧化的激活模式(Kansaku，et al. 2000)。与此一致，研究者们进一步发现，字形学习效率与大脑激活模式之间的关系模式也存在性别差异(Chen，et al. 2007)。并且，学习前梭状回激活的左侧化能够显著预测男性学习的长时保持(Dong，et al. 2008)。同时，除了字形学习，研究还发现学习前语音加工时左侧颞中回/颞上沟激活越强、右侧额下回激活越弱的被试，两周后的听力任务成绩越好(Mei，et al. 2008)。

可以看到，采用人工语言训练的方式可以有效地揭示阅读能力的个体差异及其神经机制，并且建立因果关系。然而，以人工语言为实验材料在生态学效度方面仍然存在一定的缺陷。由于词汇数量的限制，难以研究元语言意识以及一些重要的阅读效应，如邻近效应和规则效应等。另外，成人和儿童在阅读能力习得上也存在认知和神经机制的差异。

5. 研究展望

近年来，有关阅读能力个体差异的多学科研究取得了很大的进展。来自基因、行为、脑功能及脑结构的研究发现，阅读能力与大脑多个神经指标都存在关系，并且随着个体发展的不同阶段，阅读能力的神经机制也存在一定的差异。对母语和第二语言阅读能力的考察发现，二者在神经机制方面存在一致性和差异性。另外，研究发现阅读前大脑神经模式的差异可以预测后来的阅读能力。这些结果一方面大大加深了对脑与语言关系的认识，也为阅读能力的早期预测和早期干预提供了重要的研究基础。未来的研究有望在如下几个方面取得更大的突破。

第一，开展大样本研究，更加全面系统地探讨阅读能力各个成分的个体差异及其认知和神经机制。通过综合采集基因、脑、阅读能力等方面的数据，并运用复杂的数据分析方法，可以建立更加准确的阅读能力预测模型。另外，目前的研究对象主要集中在词汇水平，未来研究需加强探讨句子和篇章等水平的阅读能力的个体差异。

第二，从发展的角度深入揭示阅读能力个体差异的遗传和环境机制及其相应的神经基础。遗传和环境及其交互作用对阅读能力的获得至关重要，其中大脑发育和阅读能力发展的关系值得深入研究，这对于更加深入地揭示阅读能力个体差异的产生机制具有重要意义。

第三，开展阅读能力个体差异神经机制的跨文化研究，尤其是母语和第二语言之间的交互作用。由于受到文化背景的影响，不同文字系统可能存在不同的神经机制。已有研究开始揭示母语和第二语言阅读能力个体差异在神经机制方面的异同，今后的研究需要进一步揭示这些异同，并从同化和顺应的角度揭示其内在的机制。

第四，开展阅读能力干预训练的研究。在阅读能力的早期预测的基础上，今后的研究需要重点开展基于脑的阅读能力干预训练的研究，包括一些行为的干预方案、无损脑刺激的干预方案、脑机接口和神经反馈训练的方案以及神经药物的干预方案。另外，研究者需要关注个体对不同的训练方案的反应，从而实现个性化的阅读训练和矫正。

References 引用文献

Adams, R.B. and P. Janata. 2002. A comparison of neural circuits underlying auditory and visual object categorization. *NeuroImage* 16,2: 361–77.

Aravena, S., P. Snellings, J. Tijms, and M.W. van der Molen. 2013. A lab-controlled simulation of a letter-speech sound binding deficit in dyslexia. *Journal of Experimental Child Psychology* 115,4: 691–707.

Ashburner, J. and K.J. Friston. 2000. Voxel-based morphometry: The methods. *NeuroImage* 11,6: 805–21.

Beaulieu, C., C. Plewes, L.A. Paulson, et al. 2005. Imaging brain connectivity in children with diverse reading ability. *NeuroImage* 25,4: 1266–71.

Binder, J.R., K.A. McKiernan, M.E. Parsons, et al. 2003. Neural correlates of lexical access during visual word recognition. *Journal of Cognitive Neuroscience* 15,3: 372–93.

Binder, J. R., D. A. Medler, R. Desai, L. L. Conant, and E. Liebenthal. 2005. Some neurophysiological constraints on models of word naming. *NeuroImage* 27,3: 677–93.

Bishop, D.V., C.V. Adams, and C.F. Norbury. 2006. Distinct genetic influences on grammar and phonological short-term memory deficits: Evidence from 6-year-old twins. *Genes, Brain and Behavior* 5,2: 158–69.

Biswal, B., F.Z. Yetkin, V.M. Haughton, and J.S. Hyde. 1995. Functional connectivity in the motor cortex of resting human brain using echo-planar MRI. *Magnetic Resonance in Medicine* 34,4: 537–41.

Blackmon, K., W.B. Barr, R. Kuzniecky, et al. 2010. Phonetically irregular word pronunciation and cortical thickness in the adult brain. *NeuroImage* 51,4: 1453–8.

Bolger, D.J., C.A. Perfetti, and W. Schneider. 2005. Cross-cultural effect on the brain revisited: Universal structures plus writing system variation. *Human Brain Mapping* 25,1: 92–104.

Booth, J.R., D.D. Burman, J.R. Meyer, D.R. Gitelman, T.B. Parrish, and M.M. Mesulam. 2002. Modality independence of word comprehension. *Human Brain Mapping* 16,4: 251–61.

———. 2004. Development of brain mechanisms for processing orthographic and phonologic representations. *Journal of Cognitive Neuroscience* 16,7: 1234–49.

Brem, S., K. Bucher, P. Halder, et al. 2006. Evidence for developmental changes in the visual word processing network beyond adolescence. *NeuroImage* 29,3: 822–37.

Bright, P., H. Moss, and L.K. Tyler. 2004. Unitary vs multiple semantics: PET studies of word and picture processing. *Brain and Language* 89,3: 417–32.

Bruno, J.L., A. Zumberge, F.R. Manis, Z.L. Lu, and J.G. Goldman. 2008. Sensitivity to orthographic familiarity in the occipito-temporal region. *NeuroImage* 39,4: 1988–2001.

Brunswick, N., E. McCrory, C.J. Price, C.D. Frith, and U. Frith. 1999. Explicit and implicit processing of words and pseudowords by adult developmental dyslexics: A search for Wernicke's Wortschatz? *Brain* 122,10: 1901–17.

Burton, H., J.B. Diamond, and K.B. McDermott. 2003. Dissociating cortical regions activated by semantic and phonological tasks: An fMRI study in blind and sighted people. *Journal of Neurophysiology* 90,3: 1965–82.

Byrne, B., W.L. Coventry, R.K. Olson, et al. 2009. Genetic and environmental influences on aspects of literacy and language in early childhood: Continuity and change from preschool to Grade 2. *Journal of Neurolinguistics* 22,3: 219–36.

Cao, F., T. Bitan, T.L. Chou, D.D. Burman, and J.R. Booth. 2006. Deficient orthographic and phonological representations in children with dyslexia revealed by brain activation patterns. *Journal of Child Psychology and Psychiatry* 47,10: 1041–50.

Carter, J.C., D.C. Lanham, L.E. Cutting, et al. 2009. A dual DTI approach to analyzing white matter in children with dyslexia. *Psychiatry Research* 172,3: 215-9.

Catani, M., D.K. Jones, and D.H. Ffytche. 2005. Perisylvian language networks of the human brain. *Annals of Neurology* 57,1: 8-16.

Catani, M., R.J. Howard, S. Pajevic, and D.K. Jones. 2002. Virtual in vivo interactive dissection of white matter fasciculi in the human brain. *NeuroImage* 17,1: 77-94.

Chen, C., G. Xue, Q. Dong, et al. 2007. Sex determines the neurofunctional predictors of visual word learning. *Neuropsychologia* 45,4: 741-7.

Chen, Y., S. Fu, S.D. bIversen, S.M. Smith, and P.M. Matthews. 2002. Testing for dual brain processing routes in reading: A direct contrast of Chinese character and pinyin reading using FMRI. *Journal of Cognitive Neuroscience* 14,7: 1088-98.

Chow, B.W., C.S. Ho, S.W. Wong, M.M. Waye, and D.V. Bishop. 2011. Genetic and environmental influences on Chinese language and reading abilities. *PLOS ONE* 6,2: e16640.

Cohen, L., S. Dehaene, L. Naccache, et al. 2000. The visual word form area: Spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. *Brain* 123,2: 291-307.

Coltheart, M., K. Rastle, C. Perry, and M. Haller. 1993. Models of reading aloud: Dual-route and parallel-distributed-processing approaches. *Psychological Review* 100,4: 589-608.

Coltheart, M., K. Rastle, C. Perry, R. Langdon, and J. Ziegler. 2001. DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review* 108,1: 204-56.

Cope, N., D. Harold, G. Hill, et al. 2005. Strong evidence that KIAA0319 on chromosome 6p is a susceptibility gene for developmental dyslexia. *The American Journal of Human Genetics* 76,4: 581-91.

Cordes, D., V. Haughton, J.D. Carew, K. Arfanakis, and K. Maravilla. 2002. Hierarchical clustering to measure connectivity in fMRI resting-state data. *Magnetic Resonance Imaging* 20,4: 305-17.

Dale, A.M., B. Fischl, and M.I. Sereno. 1999. Cortical surface-based analysis, I: Segmentation and surface reconstruction. *NeuroImage* 9,2: 179-94.

Davis, O.S., Y. Kovas, N. Harlaar, et al. 2008. Generalist genes and the Internet generation: Etiology of learning abilities by web testing at age 10. *Genes, Brain and Behavior* 7,4: 455-62.

DeFries, J.C., D.W. Fulker, and M.C. LaBuda. 1987. Evidence for a genetic aetiology in reading disability of twins. *Nature* 329,6139: 537-9.

Dehaene, S., E. Dupoux, J. Mehler, et al. 1997. Anatomical variability in the cortical representation of first and second language. *Neuroreport* 8,17: 3809-15.

Dehaene, S. and L.Cohen. 2007. Cultural recycling of cortical maps. *Neuron* 56,2: 384-98.

Demb, J.B., J.E. Desmond, A.D. Wagner, et al.1995. Semantic encoding and retrieval in the left inferior prefrontal cortex: A functional MRI study of task difficulty and process specificity. *Journal of Neuroscience* 15,9: 5870-8.

Deutsch, G.K., R.F. Dougherty, R. Bammer, et al. 2005. Children's reading performance is correlated with white matter structure measured by diffusion tensor imaging. *Cortex* 41,3: 354-63.

Devlin, J.T., P.M. Matthews, and M.F. Rushworth. 2003. Semantic processing in the left inferior prefrontal cortex: A combined functional magnetic resonance imaging and transcranial magnetic stimulation study. *Journal of Cognitive Neuroscience* 15,1: 71-84.

Dong, Q., L. Mei, G. Xue, et al. 2008. Sex-dependent neurofunctional predictors of long-term maintenance of visual word learning. *Neuroscience Letters* 430,2: 87-91.

Dougherty, R.F., M. Ben-Shachar, G.K. Deutsch, et al. 2007. Temporal-callosal pathway diffusivity predicts phonological skills in children. *Proceedings of the National Academy of Sciences of the United States of America* (*PNAS*) 104,20: 8556-61.

Fiebach, C.J., A.D. Friederici, K. Muller, and D.Y. von Cramon. 2002. fMRI evidence for dual routes to the mental lexicon in visual word recognition. *Journal of Cognitive Neuroscience* 14,1: 11-23.

Fiez, J.A., D.A. Balota, M.E. Raichle, and S.E. Petersen. 1999. Effects of lexicality, frequency, and spelling-to-sound consistency on the functional anatomy of reading. *Neuron* 24,1: 205-18.

Fischl, B., M. I. Sereno, and A. M. Dale. 1999. Cortical surface-based analysis, II: Inflation, flattening, and a surface-based coordinate system. *NeuroImage* 9,2: 195–207.

Frey, S., J. S. Campbell, G. B. Pike, and M. Petrides. 2008. Dissociating the human language pathways with high angular resolution diffusion fiber tractography. *Journal of Neuroscience* 28,45: 11435–44.

Friend, A., J. C. DeFries, R. K. Olson, et al. 2009. Heritability of high reading ability and its interaction with parental education. *Behavior Genetics* 39,4: 427–36.

Friston, K.J., C.D. Frith, P.F. Liddle, and R.S. Frackowiak. 1993. Functional connectivity: The principal-component analysis of large (PET) data sets. *Journal of Cerebral Blood Flow and Metabolism* 13,1: 5–14.

Friston, K.J., L. Harrison, and W. Penny. 2003. Dynamic causal modelling. *NeuroImage* 19,4: 1273–302.

Fu, S., Y. Chen, S. Smith, S. Iversen, and P. M. Matthews. 2002. Effects of word form on brain processing of written Chinese. *NeuroImage* 17,3: 1538–48.

Gayan, J. and R.K. Olson. 2003. Genetic and environmental influences on individual differences in printed word recognition. *Journal of Experimental Child Psychology* 84,2: 97–123.

Golestani, N., N. Molko, S. Dehaene, D. LeBihan, and C. Pallier. 2007. Brain structure predicts the learning of foreign speech sounds. *Cerebral Cortex* 17,3: 575–82.

Golestani, N., T. Paus, and R.J. Zatorre. 2002. Anatomical correlates of learning novel speech sounds. *Neuron* 35,5: 997–1010.

Greicius, M. D., G. Srivastava, A. L. Reiss, and V. Menon. 2004. Default-mode network activity distinguishes Alzheimer's disease from healthy aging: Evidence from functional MRI. *PNAS* 101, 13: 4637–42.

Gurd, J.M., K. Amunts, P.H. Weiss, et al. 2002. Posterior parietal cortex is implicated in continuous switching between verbal fluency tasks: An fMRI study with clinical implications. *Brain* 125,5: 1024–38.

Hagoort, P., P. Indefrey, C. Brown, et al. 1999. The neural circuitry involved in the reading of German words and pseudowords: A PET study. *Journal of Cognitive Neuroscience* 11,4: 383–98.

Hampson, M., F. Tokoglu, Z. Sun, et al. 2006. Connectivity-behavior analysis reveals that functional connectivity between left BA39 and Broca's area varies with reading ability. *NeuroImage* 31,2: 513–9.

Hannula-Jouppi, K., N. Kaminen-Ahola, M. Taipale, et al. 2005. The axon guidance receptor gene ROBO1 is a candidate gene for developmental dyslexia. *PLOS Genetics* 1,4: e50.

Harlaar, N., F. M. Spinath, P. S. Dale, and R. Plomin. 2005. Genetic influences on early word recognition abilities and disabilities: A study of 7-year-old twins. *Journal of Child Psychology and Psychiatry* 46,4: 373–84.

Harlaar, N., P.S. Dale, and R. Plomin. 2007. From learning to read to reading to learn: Substantial and stable genetic influence. *Child Development* 78,1: 116–31.

Hawke, J.L., S.J. Wadsworth, and J.C. DeFries. 2006. Genetic influences on reading difficulties in boys and girls: The Colorado twin study. *Dyslexia* 12,1: 21–9.

He, Q., G. Xue, C. Chen, Z. L. Lu, and Q. Dong. 2013. Decoding the neuroanatomical basis of reading ability: A multivoxel morphometric study. *Journal of Neuroscience* 33,31: 12835–43.

Herbster, A.N., M.A. Mintun, R.D. Nebes, and J.T. Becker. 1997. Regional cerebral blood flow during word and nonword reading. *Human Brain Mapping* 5,2: 84–92.

Hoeft, F., A. Meyler, A. Hernandez, et al. 2007. Functional and morphometric brain dissociation between dyslexia and reading ability. *PNAS* 104,10: 4234–9.

Hoeft, F., B.D. McCandliss, J.M. Black, et al. 2011. Neural systems predicting long-term outcome in dyslexia. *PNAS* 108,1: 361–6.

Hoeft, F., T. Ueno, A.L. Reiss, et al. 2007. Prediction of children's reading skills using behavioral, functional, and structural neuroimaging measures. *Behavioral Neuroscience* 121,3: 602–13.

Horwitz, B., J.M. Rumsey, and B.C. Donohue. 1998. Functional connectivity of the angular gyrus in normal reading and dyslexia. *PNAS* 95,15: 8939–44.

Jessen, F., M. Erb, U. Klose, et al. 1999. Activation of human language processing brain regions after the presentation of random letter strings demonstrated with event-related functional magnetic resonance imaging. *Neuroscience Letters* 270,1: 13–6.

Jobard, G., F. Crivello, and N. Tzourio-Mazoyer. 2003. Evaluation of the dual route theory of reading: A metanalysis of 35 neuroimaging studies. *NeuroImage* 20,2: 693–712.

Kansaku, K., A. Yamaura, and S. Kitazawa. 2000. Sex differences in lateralization revealed in the posterior language areas. *Cerebral Cortex* 10,9: 866–72.

Klingberg, T., M. Hedehus, E. Temple, et al. 2000. Microstructure of temporo-parietal white matter as a basis for reading ability: Evidence from diffusion tensor magnetic resonance imaging. *Neuron* 25,2: 493–500.

Koyama, M.S., A. Di Martino, X.N. Zuo, et al. 2011. Resting-state functional connectivity indexes reading competence in children and adults. *Journal of Neuroscience* 31,23: 8617–24.

Kuo, W.J., T.C. Yeh, J.R. Lee, et al. 2004. Orthographic and phonological processing of Chinese characters: An fMRI study. *NeuroImage* 21,4: 1721–31.

Lai, C.S.L., S.E. Fisher, J.A. Hurst, F. Vargha-Khadem, and A.P. Monaco. 2001. A forkhead-domain gene is mutated in a severe speech and language disorder. *Nature* 413,6855: 519–23.

Lebel, C., B. Shaywitz, J. Holahan, et al. 2013. Diffusion tensor imaging correlates of reading ability in dysfluent and non-impaired readers. *Brain and Language* 125,2: 215–22.

Lei, L., J. Pan, H. Liu, et al. 2011. Developmental trajectories of reading development and impairment from ages 3 to 8 years in Chinese children. *Journal of Child Psychology and Psychiatry* 52,2: 212–20.

MacDermot, K.D., E. Bonora, N. Sykes, et al. 2005. Identification of FOXP2 truncation as a novel cause of developmental speech and language deficits. *The American Journal of Human Genetics* 76, 6: 1074–80.

Maloney, E., E.F. Risko, S. O'Malley, and D. Besner. 2009. Tracking the transition from sublexical to lexical processing: On the creation of orthographic and phonological lexical representations. *The Quarterly Journal of Experimental Psychology* (*Hove*) 62,5: 858–67.

McBride-Chang, C., F. Lam, C. Lam, et al. 2011. Early predictors of dyslexia in Chinese children: Familial history of dyslexia, language delay, and cognitive profiles. *Journal of Child Psychology and Psychiatry* 52,2: 204–11.

McCandliss, B.D., L. Cohen, and S. Dehaene. 2003. The visual word form area: Expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences* 7,7: 293–9.

McCrory, E.J., A. Mechelli, U. Frith, and C.J. Price. 2005. More than words: A common neural basis for reading and naming deficits in developmental dyslexia? *Brain* 128,2: 261–7.

McDermott, K.B., S.E. Petersen, J.M. Watson, and J.G. Ojemann. 2003. A procedure for identifying regions preferentially activated by attention to semantic and phonological relations using functional magnetic resonance imaging. *Neuropsychologia* 41,3: 293–303.

McIntosh, A.R. and F. Gonzalez-Lima. 1994. Structural equation modeling and its application to network analysis in functional brain imaging. *Human Brain Mapping* 2,1: 2–22.

McNorgan, C., A. Alvarez, A. Bhullar, J. Gayda, and J. R.Booth. 2011. Prediction of reading skill several years later depends on age and brain region: Implications for developmental models of reading. *Journal of Neuroscience* 31,26: 9641–8.

Mechelli, A., J.T. Crinion, S. Long, et al. 2005. Dissociating reading processes on the basis of neuronal interactions. *Journal of Cognitive Neuroscience* 17,11: 1753–65.

Mechelli, A., M.L. Gorno-Tempini, and C.J. Price. 2003. Neuroimaging studies of word and pseudoword reading: Consistencies, inconsistencies, and limitations. *Journal of Cognitive Neuroscience* 15,2: 260–71.

Mei, L., C. Chen, G. Xue, et al. 2008. Neural predictors of auditory word learning. *Neuroreport* 19,2:

215-9.
Mei, L., G. Xue, Z.L. Lu, et al. 2014. Artificial language training reveals the neural substrates underlying addressed and assembled phonologies. *PLOS ONE* 9,3: e93548.
Meng, H., S.D. Smith, K. Hager, et al. 2005. DCDC2 is associated with reading disability and modulates neuronal development in the brain. *PNAS* 102,47: 17053-8.
Molfese, D.L. 2000. Predicting dyslexia at 8 years of age using neonatal brain responses. *Brain and Language* 72,3: 238-45.
Newbury, D.F., L. Winchester, L. Addis, et al. 2009. CMIP and ATP2C2 modulate phonological short-term memory in language impairment. *The American Journal of Human Genetics* 85,2: 264-72.
Niogi, S.N. and B.D. McCandliss. 2006. Left lateralized white matter microstructure accounts for individual differences in reading ability and disability. *Neuropsychologia* 44,11: 2178-88.
Nosarti, C., A. Mechelli, D.W. Green, and C.J. Price, 2010. The impact of second language learning on semantic and nonsemantic first language reading. *Cerebral Cortex* 20,2: 315-27.
Odegard, T.N., E.A. Farris, J. Ring, R. McColl, and J. Black. 2009. Brain connectivity in non-reading impaired children and children diagnosed with developmental dyslexia. *Neuropsychologia* 47,8-9: 1972-7.
Paulesu, E., E. McCrory, F. Fazio, et al. 2000. A cultural effect on brain function. *Nature Neuroscience* 3,1: 91-6.
Petrill, S.A., L.A. Thompson, K. Deater-Deckard, L.S. Dethorne, and C. Schatschneider. 2006. Genetic and environmental effects of serial naming and phonological awareness on early reading outcomes. *Journal of Educational Psychology* 98,1: 112-21.
Poldrack, R.A., A.D. Wagner, M.W. Prull, et al. 1999. Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *NeuroImage* 10,1: 15-35.
Price, C.J. 2000. The anatomy of language: Contributions from functional neuroimaging. *Journal of Anatomy* 197,3: 335-59.
Price, C.J. and K.J. Friston. 1997. The temporal dynamics of reading: A PET study. *Proceedings of the Royal Society B: Biological Sciences* 264,1389: 1785-91.
Pugh, K. 2006. A neurocognitive overview of reading acquisition and dyslexia across languages. *Developmental Science* 9,5: 448-50; discussion 451-43.
Pugh, K.R., W.E. Mencl, A.R. Jenner, et al. 2000a. Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental Retardation and Developmental Disabilities Research Reviews* 6,3: 207-13.
Pugh, K.R., W.E. Mencl, B.A. Shaywitz, et al. 2000b. The angular gyrus in developmental dyslexia: Task-specific differences in functional connectivity within posterior cortex. *Psychological Science* 11,1: 51-6.
Qiu, D., L.H. Tan, K. Zhou, and P.L. Khong. 2008. Diffusion tensor imaging of normal white matter maturation from late childhood to young adulthood: Voxel-wise evaluation of mean diffusivity, fractional anisotropy, radial and axial diffusivities, and correlation with reading development. *NeuroImage* 41,2: 223-32.
Richards, T., J. Stevenson, J. Crouch, et al. 2008. Tract-based spatial statistics of diffusion tensor imaging in adults with dyslexia. *American Journal of Neuroradiology* 29,6: 1134-9.
Rimrodt, S.L., D.J. Peterson, M.B. Denckla, W.E. Kaufmann, and L.E. Cutting. 2010. White matter microstructural differences linked to left perisylvian language network in children with dyslexia. *Cortex* 46,6: 739-49.
Roebroeck, A., E. Formisano, and R. Goebel. 2005. Mapping directed influence over the brain using Granger causality and fMRI. *NeuroImage* 25,1: 230-42.
Ronnberg, J., M. Rudner, and M. Ingvar. 2004. Neural correlates of working memory for sign language. *Cognitive Brain Research* 20,2: 165-82.
Rumsey, J.M., B. Horwitz, B.C. Donohue, et al. 1997. Phonological and orthographic components of

word recognition—A PET-rCBF study. *Brain* 120,5: 739–59.

Schlaggar, B. L. and B. D. McCandliss. 2007. Development of neural systems for reading. *Annual Review of Neuroscience* 30,475–503.

Seidenberg, M.S. and J.L. McClelland. 1989. A distributed, developmental model of word recognition and naming. *Psychological Review* 96,4: 523–68.

Shaywitz, B.A., S.E. Shaywitz, K.R. Pugh, et al. 2002. Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry* 52,2: 101–10.

Shaywitz, S.E. and B.A. Shaywitz. 2003. Dyslexia (specific reading disability). *Pediatrics in Review* 24,5: 147–53.

———. 2005. Dyslexia (specific reading disability). *Biological Psychiatry* 57,11: 1301–9.

Shaywitz, S.E., B.A. Shaywitz, K.R. Pugh, et al. 1998. Functional disruption in the organization of the brain for reading in dyslexia. *PNAS* 95,5: 2636–41.

Simos, P.G., J.I. Breier, J.M. Fletcher, et al. 2000a. Brain activation profiles in dyslexic children during non-word reading: A magnetic source imaging study. *Neuroscience Letters* 290,1: 61–5.

Simos, P.G., J.I. Breier, J.M. Fletcher, E. Bergman, and A.C. Papanicolaou. 2000b. Cerebral mechanisms involved in word reading in dyslexic children: A magnetic source imaging approach. *Cerebral Cortex* 10,8: 809–16.

Simos, P. G., J. I. Breier, J. M. Fletcher, et al. 2002. Brain mechanisms for reading words and pseudowords: An integrated approach. *Cerebral Cortex* 12,3: 297–305.

Siok, W.T., Z. Niu, Z. Jin, C.A. Perfetti, and L.H. Tan. 2008. A structural-functional basis for dyslexia in the cortex of Chinese readers. *PNAS* 105,14: 5561–6.

Steinbrink, C., K. Vogt, A. Kastrup, et al. 2008. The contribution of white and gray matter differences to developmental dyslexia: Insights from DTI and VBM at 3.0 T. *Neuropsychologia* 46,13: 3170–8.

Taipale, M., N. Kaminen, J. Nopola-Hemmi, et al. 2003. A candidate gene for developmental dyslexia encodes a nuclear tetratricopeptide repeat domain protein dynamically regulated in brain. *PNAS* 100,20: 11553–8.

Tan, L.H., L. Chen, V. Yip, et al. 2011. Activity levels in the left hemisphere caudate-fusiform circuit predict how well a second language will be learned. *PNAS* 108,6: 2540–4.

Turkeltaub, P.E., L. Gareau, D.L. Flowers, T.A. Zeffiro, and G.F. Eden. 2003. Development of neural mechanisms for reading. *Nature Neuroscience* 6,7: 767–73.

van der Mark, S., K. Bucher, U. Maurer, et al. 2009. Children with dyslexia lack multiple specializations along the visual word-form (VWF) system. *NeuroImage* 47,4: 1940–9.

Vandermosten, M., B. Boets, H. Poelmans, et al. 2012a. A tractography study in dyslexia: Neuroanatomic correlates of orthographic, phonological and speech processing. *Brain* 135,3: 935–48.

Vandermosten, M., B. Boets, J. Wouters, and P. Ghesquiere. 2012b. A qualitative and quantitative review of diffusion tensor imaging studies in reading and dyslexia. *Neuroscience and Biobehavioral Reviews* 36(6), 1532–52.

Vellutino, F.R., J.M. Fletcher, M.J. Snowling, and D.M. Scanlon. 2004. Specific reading disability (dyslexia): What have we learned in the past four decades? *Journal of Child Psychology and Psychiatry* 45,1: 2–40.

Vernes, S.C., D.F. Newbury, B.S. Abrahams, et al. 2008. A functional genetic link between distinct developmental language disorders. *The New England Journal of Medicine* 359,22: 2337–45.

Vigneau, M., V. Beaucousin, P.Y. Herve, et al. 2006. Meta-analyzing left hemisphere language areas: Phonology, semantics, and sentence processing. *NeuroImage* 30,4: 1414–32.

Wang, X., Z. Han, Y. He, L. Liu, and Y. Bi. 2012. Resting-state functional connectivity patterns predict Chinese word reading competency. *PLOS ONE* 7,9: e44848.

Warburton, E., R.J. Wise, C.J. Price, et al. 1996. Noun and verb retrieval by normal subjects. Studies with PET. *Brain* 119,1: 159–79.

Welcome, S.E., C. Chiarello, P.M. Thompson, and E.R. Sowell. 2011. Reading skill is related to individual differences in brain structure in college students. *Human Brain Mapping* 32,8: 1194-205.

White, H. and X. Lu. 2010. Granger causality and dynamic structural systems. *Journal of Financial Econometrics* 8, 193-243.

Wong, P.C., C.M. Warrier, V.B. Penhune, et al. 2008. Volume of left Heschl's Gyrus and linguistic pitch learning. *Cerebral Cortex* 18,4: 828-36.

Wong, P.C., T.K. Perrachione, and T.B. Parrish. 2007. Neural characteristics of successful and less successful speech and word learning in adults. *Human Brain Mapping* 28,10: 995-1006.

Xiong, J., S. Rao, J.H. Gao, M. Woldorff, and P.T. Fox. 1998. Evaluation of hemispheric dominance for language using functional MRI: A comparison with positron emission tomography. *Human Brain Mapping* 6,1: 42-58.

Xue, G., C. Chen, Z. Jin, and Q. Dong. 2006a. Language experience shapes fusiform activation when processing a logographic artificial language: An fMRI training study. *NeuroImage* 31,3: 1315-26.

———. 2006b. Cerebral asymmetry in the fusiform areas predicted the efficiency of learning a new writing system. *Journal of Cognitive Neuroscience* 18,6: 923-31.

Zatorre, R.J., E. Meyer, A. Gjedde, and A.C. Evans. 1996. PET studies of phonetic processing of speech: Review, replication, and reanalysis. *Cereb Cortex* 6,1: 21-30.

Zhang, M., C. Chen, G. Xue, et al. 2014. Language-general and -specific white matter microstructural bases for reading. *NeuroImage* 98,435-41.

Zhang, M., J. Li, C. Chen, L. Mei, et al. 2013a. The contribution of the left mid-fusiform cortical thickness to Chinese and English reading in a large Chinese sample. *NeuroImage* 65, 250-6.

Zhang, M., J. Li, C. Chen, G. Xue, et al. 2013b. Resting-state functional connectivity and reading abilities in first and second languages. *NeuroImage* 84C,546-53.

Zhang, Y., J. Li, T. Tardif, et al. 2013c. Association of the DYX1C1 dyslexia susceptibility gene with orthography in the Chinese population. *PLOS ONE* 7,9: e42969.

Zhang, Y., T. Tardif, H. Shu, et al. 2012. Phonological skills and vocabulary knowledge mediate socioeconomic status effects in predicting reading outcomes for Chinese children. *Developmental Psychology* 49,4: 665-71.

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