Competitive Developmental Mechanism of Complementary Hemispheric Lateralization Patterns in Text and Face Recognition (Postprint)

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Abstract

In the adult brain, the left VWFA is more sensitive to orthographic information, while the right FFA preferentially processes face information. However, the developmental mechanisms underlying this complementary lateralization pattern remain to be elucidated. The neuronal recycling hypothesis posits that during literacy acquisition, word recognition competes with face representation for neural processing resources in the left FG, leading to left lateralization of the VWFA for word recognition and driving right lateralization of the FFA for face recognition. The distributed hemispheric organization perspective proposes three principles of neural computational processing, attempting to systematically elucidate the multi-level bidirectional dynamic processing mechanisms underlying the competitive development of lateralization for words and faces. Recently, research on the structural partitioning and functional characteristics of the FG has yielded new findings, based on which a multi-dimensional computational processing model for word and face recognition has been constructed. Therefore, it is necessary to systematically investigate the cognitive neural processing mechanisms underlying the competitive development of the hemispheric lateralization complementary pattern for word and face recognition, based on the neuronal recycling hypothesis and the distributed hemispheric organization perspective, and in conjunction with the structural and functional characteristics of the FG and recent research evidence. Future research should further investigate the cortical spatial localization and functional neuroarchitectural basis of competitive processing between words and faces, the processing mechanisms of competition between Chinese characters and faces, the developmental mechanisms of right lateralization for face recognition, and the mechanisms of brain plasticity changes resulting from learning to read numbers and musical notes.

Full Text

Preamble

Mechanism of Competitive Development of Hemispheric Lateralization Complementary Pattern for Word and Face Recognition

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Abstract: The left visual word form area (VWFA) in the adult brain is more sensitive to orthographic information, while the right fusiform face area (FFA) preferentially processes facial information. However, the developmental mechanism underlying this complementary pattern of hemispheric lateralization remains to be elucidated. The neuronal recycling hypothesis posits that during literacy acquisition, word recognition competes with face representation for neural processing resources in the left fusiform gyrus (FG), leading to left-hemispheric lateralization of the VWFA and driving right-hemispheric lateralization of the FFA. The distributed account of hemispheric organization proposes three key neural computational principles to systematically explain the multilevel, bidirectional dynamic processing mechanism of this competitive lateralization development. Recent research on the cytoarchitectonic areas and functional characteristics of the FG has yielded valuable new findings, enabling the construction of a multidimensional computational model of word and face recognition. Therefore, it is necessary to systematically examine the cognitive neural processing mechanisms underlying the competitive development of the complementary hemispheric lateralization pattern for word and face recognition, based on the neuronal recycling hypothesis and distributed account, combined with the structural and functional features of the FG and recent empirical evidence. Future research should further investigate the cortical spatial locations and functional neurohistological basis of competitive processing between words and faces, the processing mechanisms of competition between Chinese characters and faces, the developmental mechanism of right-hemispheric specialization for face recognition, and the mechanisms of brain plasticity changes resulting from learning to read numbers and musical notation.

Keywords: visual word form area, fusiform face area, complementary pattern of hemispheric lateralization, mechanism of competitive development, multilevel and bidirectional dynamic processing
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Both word and face recognition rely on expert visual processing to make fine-grained discriminations among highly similar stimuli with subtle differences [**?**, **?**]. Neuroimaging [**?**, **?**, **?**], electrophysiological [**?**, **?**, **?**], and neuropsychological studies [**?**, **?**, **?**] in adults have shown that the critical brain regions for

word and face recognition are located in two adjacent subregions of the fusiform gyrus (FG) within the ventral occipito-temporal cortex (vOTC), yet they exhibit a complementary pattern of hemispheric lateralization [?, ?, ?, ?, ?]. Specifically, the left hemisphere' s visual word form area (VWFA) is more sensitive to orthographic information, while the right hemisphere' s fusiform face area (FFA) preferentially processes facial information [?, ?, ?, ?, ?]. However, the developmental mechanism underlying this mature pattern of complementary lateralization remains to be clarified.

Notably, Dehaene and colleagues [?, ?, ?, ?, ?] proposed the neuronal recycling hypothesis to explain the developmental mechanism of this complementary hemispheric lateralization between the VWFA and FFA. This hypothesis suggests that during literacy acquisition, word recognition may compete for neural processing resources in the left FG that were originally used for face representation, leading to left-hemispheric lateralization of the VWFA and driving right-hemispheric lateralization of the FFA. Subsequently, Behrmann and Plaut [?, ?, ?, ?] adopted a distributed account of hemispheric organization to systematically articulate the neural computational principles underlying word and face recognition, elucidating the neural mechanisms of competitive development of the complementary lateralization pattern between the VWFA and FFA. Recent research on the cytoarchitectonic areas and functional characteristics of the FG has yielded valuable new findings, providing the necessary neural structural and histological foundation for clarifying this competitive developmental mechanism. Thus, it is essential to further explore the cognitive neural mechanisms underlying the competitive development of the complementary hemispheric lateralization pattern for word and face recognition, based on the neuronal recycling hypothesis and distributed account, combined with the structural and functional features of the FG. Such investigations are not only theoretically significant for revealing the brain plasticity mechanisms underlying the development of lateralization and their interrelationships in word and face processing, but also have practical value for guiding literacy instruction, artificial intelligence simulation of word and face recognition, and clinical treatment applications.

To this end, this paper first introduces the neuronal recycling hypothesis and related evidence, explaining how competitive processing between literacy acquisition and face representation in the left FG may lead to the complementary lateralization pattern in word and face recognition. It then elaborates on the three neural computational principles of word and face recognition, demonstrating that the lateralization competition is a bidirectional dynamic process occurring across multiple hierarchical structures in the vOTC. Subsequently, the structural and functional areas of the FG are introduced, and a multidimensional computational model based on the medial-lateral and posterior-anterior computational axes is presented to preliminarily clarify the cognitive neural mechanisms of the multilevel, bidirectional dynamic processing underlying the competitive lateralization development of the VWFA and FFA. Finally, future research directions and important questions are discussed.

2. Neuronal Recycling Hypothesis of Literacy Acquisition and Related Evidence

Writing is one of humanity' s most important cultural inventions. Written works first appeared in Babylon approximately 5,400 years ago [**?**, **?**], and until about 200 years ago, literacy remained confined to a small segment of the population [**?**, **?**]. Dehaene and colleagues [**?**, **?**, **?**, **?**, **?**] argued that the brain has not had sufficient time to evolve specialized neural systems for reading, and that literacy must therefore repurpose or "recycle" cortical areas originally serving more ancient functions—without any genetic recombination—by leveraging brain plasticity. This theory is known as the neuronal recycling hypothesis [**?**, **?**]. The vOTC is a convergence zone specialized for recognizing visual stimuli from different domains, including faces, locations, bodies, and objects [**?**, **?**]. Because face-selective areas require longer developmental periods and continue to exhibit structural and functional changes until adulthood, they remain more plastic than other visual stimulus-selective areas (e.g., location-selective areas) [**?**, **?**]. Consequently, literacy acquisition may compete with face processing for neural resources in the left FG, ultimately repurposing neurons previously used for face recognition to serve word recognition, resulting in left-hemispheric lateralization of the VWFA. Meanwhile, face recognition gradually shifts to the right FG, leading to right-hemispheric lateralization of the FFA [**?**, **?**].

Substantial evidence supports the neuronal recycling hypothesis. First, literacy acquisition in children leads to the emergence of the VWFA in the left FG, while the FFA develops in the right FG. Functional magnetic resonance imaging (fMRI) studies have shown that when children acquire letter knowledge, the left FG exhibits increasingly stronger responses to letters while its responses to faces concurrently weaken [**?**, **?**, **?**]. Moreover, as reading performance improves, neural activity in the right FG to faces significantly increases [**?**, **?**, **?**]. Behavioral experiments and event-related potential (ERP) studies have also demonstrated that children show a right visual field-left hemisphere advantage for word processing from early stages of reading acquisition, while the left visual field-right hemisphere advantage for face processing is not evident in children and adolescents, though its degree of lateralization positively correlates with reading comprehension ability [**?**, **?**]. Additionally, the amplitude of left N170 evoked by words in 7-11-year-old children positively correlates with the amplitude of right N170 evoked by faces [**?**, **?**]. These findings suggest that the hemispheric lateralization of word and face recognition may develop jointly.

Second, literacy acquisition in adulthood induces similar hemispheric lateralization changes in word and face recognition as observed in childhood. Dehaene et al. [**?**, **?**] conducted an fMRI study comparing illiterate adults, former illiterates (who lacked early education but acquired basic literacy in adulthood), and skilled readers (who acquired literacy early). They found that illiterates showed no response to letter strings in the left VWFA but exhibited strong activation to faces. As literacy improved from former illiterates to skilled readers, the left VWFA' s response to faces decreased, while the right FFA' s response to faces

increased. ERP studies by Pegado et al. [?, ?] also revealed that as reading ability improved from illiterate adults to former illiterates to skilled readers, the left-lateralization of N170 evoked by letter strings became stronger, while the right-lateralization of N170 evoked by faces became more pronounced.

Third, language lateralization in left-handers determines the developmental lateralization of face processing. Dundas et al. [?, ?] found that in right-handers, the amplitude of N170 evoked by words in the left hemisphere positively correlated with the amplitude of N170 evoked by faces in the right hemisphere, but this pattern was absent in left-handers. Left-handers generally exhibit right-hemisphere language dominance or weak left-hemisphere language dominance [?, ?, ?]. Since words in the left visual cortex do not exert sufficient pressure to drive face lateralization to the right, left-handers tend to show bilateral FFA activation [?, ?]. Gerrits et al. [?, ?] further distinguished left-handers with right-hemisphere language dominance from those with left-hemisphere language dominance using fMRI, finding opposite lateralization patterns: the former showed right-lateralized word processing and left-lateralized face processing, while the latter showed the reverse pattern. This indicates that when left-handers have right-hemisphere language dominance, words and faces may compete for neural processing resources in the right FG, suggesting that such competition always occurs in the language-dominant hemisphere.

Fourth, developmental neurological disorders or hemispheric lesions affect the competitive processing of words and faces. ERP studies of developmental dyslexia (DD) and congenital prosopagnosia (CP) [?, ?] found that individuals with DD showed no lateralization advantage for N170 evoked by either words or faces, whereas individuals with CP showed only left-lateralized N170 for words. One possible explanation is that individuals with DD lose word recognition ability, preventing subsequent face representation from receiving competitive pressure from words in the left hemisphere, resulting in no hemispheric advantage for either words or faces. In contrast, face recognition deficits in CP only impede the right-lateralization of face representation without affecting the left-lateralized development of word recognition. A 3-year longitudinal fMRI study tracking a patient (U.D.) who underwent right vOTC resection [?, ?] found that at the first scan (age 7 years 10 months) after surgery at age 6 years 9 months, only the VWFA was detected in the left vOTC. However, by the fourth scan (age 10 years 10 months), both the VWFA and FFA were detectable in the left vOTC. Compared to control subjects, U.D.' s VWFA was significantly shifted laterally, while the activation extent and range of the FFA increased with age and were located more medially than normal [?, ?]. This demonstrates that when faces need to reuse the left FG cortex, they similarly compete with words for neural processing resources.

The evidence collectively demonstrates that literacy acquisition may compete with face representation for neural processing resources in the left FG, causing structural and functional reorganization of the FG across hemispheres and ultimately leading to left-lateralization of the VWFA and right-lateralization of the

FFA. However, this explanation of the competitive lateralization relationship remains at the level of overall FG structure and function, and its interpretation of the competitive processing mechanism based on correlations between VWFA and FFA lateralization is largely speculative. Therefore, it is necessary to investigate the detailed processing mechanisms underlying the lateralization competition between these two brain regions.

3. Distributed Account of Hemispheric Organization

Behrmann and Plaut [?, ?, ?, ?] proposed a distributed account of hemispheric organization, arguing that the hemispheric organization of word and face recognition follows three key neural computational principles: (1) multilevel distribution of representations and knowledge; (2) competitive and cooperative coexistence of representations; and (3) localization of spatial distribution in brain regions. First, representations of words and faces are distributed across multiple levels, from the primary visual cortex (V1) that processes local retinal information to the anterior temporal cortex that processes more holistic, object-based, or semantic information [?, ?, ?]. Moreover, knowledge representations of their associated features depend on synaptic connection strengths or patterns within and between different hierarchical brain regions. Learning and experience can not only alter synaptic connection strengths or representation patterns but may also recruit additional neurons and brain areas to refine and specialize representations [?, ?]. Second, although words and faces belong to different domains of visual stimuli, their recognition both depends on high-acuity vision [?, ?, ?] and extensive learning [?, ?]. On one hand, both types of representations must cooperate with central visual information representations, causing them to compete for cortical spatial resources in adjacent areas that encode foveal retinal information projections [?, ?, ?, ?]. On the other hand, because the systematic or consistent differences in feature-related knowledge representations across hierarchical levels are substantial, when a cortical area represents face information, it becomes unsuitable for representing word information, leading to face and word knowledge being represented in different cortical regions [?, ?]. Third, during evolution, brain tissue requires sufficient neuronal connections to support necessary information processing, yet the total amount of axonal fibers is constrained by cranial volume. Therefore, spatial localization achieved through minimization of axonal length can not only reduce axonal volume but also avoid unnecessary errors from increased signal transmission distances. Consequently, on the cortical map, adjacent cortical areas are more likely to develop cooperative representational relationships, while areas with competitive representational relationships maintain a certain distance. To minimize synaptic connection length, the cortical area representing orthographic words may be constrained to the hemisphere adjacent to language-related brain areas (especially phonological processing regions). Since language representation is left-lateralized in most individuals, and there is colateralization between word and language processing networks [?, ?, ?], word representation also tends to be left-lateralized. Finally, as reading experience increases, the left vOTC (VWFA) becomes increasingly

specialized for representing word information [?, ?], which intensifies the competition between words and faces in this region. This causes bilateral face representation in preschool children to become increasingly dependent on the right vOTC (FFA) with literacy acquisition [?, ?, ?].

From the distributed account perspective, the competitive lateralization processing of words and faces may be a bidirectional dynamic process occurring across multiple hierarchical structures in the vOTC, constrained by bottom-up sensory input from the V1 region and modulated by top-down information processing from higher cortical areas (e.g., language regions). At lower processing levels, word and face recognition share bottom-up high-acuity visual information, causing them to compete for cortical spatial resources in early perception and initiating the left-lateralization of the VWFA and right-lateralization of the FFA. At higher processing levels, this early competition is modulated by top-down information processing driven by learning and experience, leading to the development of lateralization for word and face recognition. Notably, recent research on the cytoarchitectonic areas and functional characteristics of the FG has made important progress, providing possibilities for clarifying the cognitive neural mechanisms of this multilevel, bidirectional dynamic processing. The following sections systematically examine the relationship between the FG' s structure and functional areas and the competitive lateralization development of the VWFA and FFA.

4. Structure and Functional Areas of the FG and Their Relationship with the Competitive Lateralization Development of the VWFA and FFA

4.1 Four Cytoarchitectonic and Functional Areas of the FG

The FG is a critical structure in the vOTC connecting the ventral occipital cortex (VOC) and ventral temporal cortex (VTC). It is laterally bounded by the occipitotemporal sulcus (OTS), medially by the collateral sulcus (CoS), posteriorly by the posterior transverse collateral sulcus (ptCoS), and centrally by the anterior tip of the mid-fusiform sulcus (MFS) [?, ?, ?, ?, ?, ?] [Figure 1: see original paper]. Research has shown that the MFS longitudinally divides the FG into distinct medial-lateral structural and functional areas that align with, overlap, or are nested within the MFS [?, ?] [Figure 1: see original paper]. Specifically, FG1, located medially and extending toward the CoS, and FG2, located laterally and extending toward the OTS, are adjacent to the posterior occipital cortex area hOc4v [?, ?] [Figure 1: see original paper]. Functionally, FG1 serves as a transitional area between early visual cortex (V1, V2/V3, and V4) and higher visual cortex (VTC), while FG2 is a visual cortical associative region [?, ?, ?] responsible for preliminary perceptual integration of stimuli [?, ?]. Neurohistological and receptor mapping studies have further revealed that the mid-anterior FG can be divided into FG3 and FG4 by the MFS [Figure 1: see original paper]. FG3, located in the anterior part of FG1, contains the collat-

eral sulcus location-selective area (Cos-places) [?, ?, ?], whereas FG4, located in the anterior part of FG2, primarily processes object identity and meaning [?, ?, ?, ?].

Importantly, based on the cytoarchitectonic areas and functional characteristics of the FG, Weiner, Barnett, and colleagues [?, ?, ?] constructed a multidimensional computational model comprising a medial-lateral axis and a posterior-anterior axis [Figure 2: see original paper]. The medial-lateral axis is a domain-specific computational axis that physically isolates processing regions for different domains, enabling effective parallel processing of domain-specific information. In contrast, the posterior-anterior axis is a computational axis of hierarchical transformation that performs a series of continuous hierarchical computations across posterior-anterior cortex to achieve behaviorally relevant representations [?, ?, ?]. In this model, word and face recognition areas are distributed in the lateral FG areas FG2 and FG4, which preferentially process foveal visual input and are suitable for processing high-acuity visual information and fine-grained stimulus discrimination. Specifically, FFA-1 and VWFA-1 in FG2 are distributed in an overlapping medial-lateral pattern, while FFA-2 and VWFA-2 in FG4 also show a medial-lateral distribution but are separated by the fusiform body area (FBA) [Figure 2: see original paper]. Based on this model, visual information for faces and words undergoes preliminary feature processing in early visual cortex, then enters FG2 via FG1, and subsequently transmits from FFA-1 and VWFA-1 to FFA-2 and VWFA-2, respectively, to complete the hierarchical and domain-specific processing of face and word recognition [Figure 2: see original paper]. Thus, word and face recognition areas emerge and develop dynamically along the medial-lateral and posterior-anterior axes of the FG.

4.2 Early Competitive Processing Between VWFA-1 and FFA-1 in FG2

FG2 receives early visual cortex information transmitted from FG1 and performs perceptual representation based on the invariant shape of stimuli [?, ?, ?, ?]. Although word and face recognition belong to different stimulus domains, both depend on high-acuity foveal visual input to achieve high-resolution, shape-invariant perception [?, ?, ?, ?]. Evidence shows that FG2 not only preferentially processes foveal visual information [?, ?] but also responds to both words and faces [?, ?, ?], with activation zones for both overlapping in areas near foveal projection cortex [?, ?, ?]. Importantly, FG1 shows strong co-activation with early visual cortex and relatively symmetric interhemispheric function [?, ?], whereas FG2 begins to exhibit some degree of functional asymmetry for words and faces, with words eliciting left FG2 co-activation with reading-related brain regions and faces eliciting right FG2 co-activation with face processing-related regions [?, ?, ?]. VWFA-1 is localized in the left FG2, while FFA-1 appears more frequently in the right FG2 [?, ?]. Thus, word and face recognition share fine-grained visual input from the fovea in FG2 [?, ?, ?], causing literacy acqui-

sition to compete with face representation for early perceptual cortical spatial resources in FG2 [?, ?, ?, ?]. This competition initiates the differentiation of distinct hemispheric lateralization representation systems for word and face recognition in FG2 [?, ?].

4.3 Modulation of Early Competitive Processing by Lateralized Connectivity of VWFA-2 and FFA-2 with Relevant Brain Networks

FG2 is primarily constrained by bottom-up visual input processing; therefore, the left-lateralization of VWFA-1 and right-lateralization of FFA-1 resulting from early competition are mainly related to perceptual feature processing of words and faces [?, ?]. In contrast, VWFA-2 and FFA-2 in FG4 not only receive early lateralized information transmitted from VWFA-1 and FFA-1 but are also modulated by top-down information processing through connectivity with relevant brain networks driven by learning and experience. Connectivity refers to the degree of information exchange between cortical regions, including structural and functional connectivity [?, ?]. Structurally, VWFA-2 and FFA-2 connect to non-visual system brain regions through lateralized domain-specific connectivity [?, ?]. On one hand, VWFA-2 establishes strong connections with the frontotemporal network related to speech production and phonological representation (such as Broca' s area and the planum temporale) via the left arcuate fasciculus (AF) [?, ?, ?, ?, ?, ?]. On the other hand, FFA-2 connects to the extended face network responsible for face memory, social cognition, and emotional processing (including the right anterior temporal cortex, superior temporal sulcus, medial prefrontal cortex, and amygdala) via the right inferior longitudinal fasciculus (ILF) and inferior fronto-occipital fasciculus (IFOF) [?, ?, ?, ?]. Importantly, as reading experience or ability improves, the lateralized connectivity of VWFA-2 with relevant brain networks strengthens, as does its selective response to words [?, ?, ?]. For example, literacy acquisition increases the fractional anisotropy (FA) of the left posterior AF [?, ?], which correlates not only with VWFA-2 activation levels in response to letter strings but also with top-down modulation of VWFA-2 activation by the inferior frontal gyrus and left planum temporale during spoken word processing [?, ?]. Only left AF FA values correlate positively with reading ability [?, ?], suggesting that structural changes in the left AF may be related to the development of the grapheme-phoneme conversion pathway in literacy acquisition [?, ?, ?]. Similarly, face recognition ability correlates positively with FA values in the right ILF connecting FFA-2 [?, ?], while CP patients show compromised integrity in the right ILF and IFOF, with FA values in the right hemisphere correlating negatively with face recognition error rates [?, ?]. This suggests that the right ILF and IFOF may be two critical pathways for integrating holistic structural information of faces with emotional and memorial features [?, ?].

Notably, these lateralized connections are pre-existing in the brain, and learning experience with words or faces can shape word- or face-selective areas by altering the connectivity of relevant brain networks, thereby predicting their

emergence in children or adult individuals [**?**, **?**]. Literacy acquisition strengthens the connectivity between VWFA-2 and the left-lateralized language network, which in turn intensifies the early competition between words and faces in the left hemisphere, accelerating the establishment of left-lateralized word recognition and driving the development of right FFA-2. Simultaneously, accumulated face experience enhances the right-lateralized connectivity of FFA-2 with relevant brain networks, leading to the gradual establishment of right-lateralized face recognition. This learning- and experience-driven processing primarily occurs in the later stages of word or face perception and influences the competitive hemispheric lateralization development of words and faces in a top-down manner.

5. Summary and Outlook

Over the past 10-20 years, research on the complementary pattern of hemispheric lateralization for word and face recognition and its developmental mechanisms has attracted considerable attention. Although substantial evidence supports the neuronal recycling hypothesis—that the human brain competes with face representation for neural spatial resources in the left FG during literacy acquisition, resulting in left-lateralized VWFA and driving right-lateralized FFA —the cortical competitive mechanisms underlying this lateralization have only recently become clear. On one hand, the lateralization competition between word recognition and face representation is a bidirectional dynamic process occurring across multiple hierarchical structures in the vOTC. On the other hand, the four cytoarchitectonic and functional areas of the FG distinguished by the MFS, and the multidimensional computational model constructed based on them, provide possibilities for elucidating the bidirectional competitive processing mechanisms underlying the complementary lateralization development of the VWFA and FFA. Integrating existing theoretical models and research evidence, this paper outlines a schematic diagram of the multilevel, bidirectional dynamic processing mechanism of the competitive development of hemispheric lateralization for word and face recognition [Figure 3: see original paper]. Along the posterior-anterior axis of the FG, FG2 in the posterior lateral FG primarily receives bottom-up input from early visual cortex. Because fine-grained recognition of both words and faces depends on high-acuity visual information from the fovea, they share early perceptual processing resources and compete for cortical space in FG2, leading to the initial emergence of VWFA-1 (laterally along the medial-lateral axis) in the left hemisphere and FFA-1 (medially along the medial-lateral axis) in the right hemisphere. As literacy acquisition and face recognition experience accumulate, processing of word or face information transitions from VWFA-1 and FFA-1 in FG2 to VWFA-2 (laterally) and FFA-2 (medially) in FG4 in the mid-lateral FG. Since literacy acquisition strengthens the connectivity between VWFA-2 and the left-hemisphere language network, this top-down lateralized modulation intensifies the competitive processing between words and faces, resulting in stronger left-lateralization of VWFA-2 and accelerated right-lateralization of FFA-2. Meanwhile, face learning experience

also strengthens the right-lateralized connectivity of FFA-2 with relevant brain networks, leading to stronger right-lateralization of FFA-2. Thus, the competitive development of the complementary pattern of hemispheric lateralization for word and face recognition is a bidirectional dynamic process occurring across multiple dimensions of the FG.

[Figure 3: see original paper]

Although the competitive developmental mechanism of the complementary lateralization pattern for word and face recognition has been preliminarily elucidated, several key issues and directions require further investigation.

First, the cortical spatial mechanism of competitive processing between words and faces. Most evidence supporting the neuronal recycling hypothesis is based on between-group comparisons across different age groups and reading levels, which may lack precision. Averaging or smoothing data within groups may cause cortical response zones for different categories of stimuli to appear overlapping, when in fact these brain regions may occupy clearly demarcated areas in different individuals [**?**, **?**]. Therefore, longitudinal studies tracking the same group of children at different stages of literacy acquisition are needed to provide evidence of changing activation levels in different cortical selective regions. Dehaene-Lambertz et al. [**?**, **?**] conducted 6-7 fMRI scans (approximately 2 months apart) in 10 children from before school entry through the first year of schooling, finding no negative correlation between VWFA and FFA activation within the left hemisphere. However, they did find that right FFA activation levels increased with reading scores. Importantly, during this process, the VWFA encroached upon neuronal patches with weak and unstable specificity for tools located near face representation areas [**?**, **?**]. Based on this, Dehaene-Lambertz et al. [**?**, **?**] proposed a revised neuronal recycling hypothesis, suggesting that with children' s literacy acquisition, the number of neuronal patches responsive to words in the left FG continuously increases, which blocks the expansion of object- or face-responsive patches and causes face recognition to be gradually taken over by the right FG. To further examine the effects of brain maturation and reading level on this effect, Feng et al. [**?**, **?**] conducted fMRI scans in 6-year-old children who had not yet learned to read, 6-year-olds who had just begun reading, and skilled 9-year-old readers, with results supporting this blocking model. That is, words do not directly compete with faces but instead block the slow development of faces in the left hemisphere, thereby enhancing right-lateralization of faces. These results better explain the marginal competition effect found by Dehaene et al. [**?**, **?**], where although FFA peak activation was not affected by reading ability, competitive effects could be observed in voxels 12 or 16 mm from the FFA peak—specifically, left FFA activation decreased as reading scores increased. Future studies should employ high-resolution ($<$ 1 mm) fMRI technology [**?**, **?**, **?**] to examine voxel-by-voxel changes in 1 mm increments from rings centered on the FFA peak, to determine the precise cortical spatial location of competition and investigate whether words compete directly with faces or block the left-hemisphere development of face representation.

Second, the functional neurohistological basis of competitive lateralization processing between words and faces. Although evidence shows that both FG2 and FG4 are involved in word and face recognition, the functional neurohistology of how these regions participate in competitive processing requires further investigation. First, the high density of large pyramidal cells in FG2 may be related to high-acuity foveal computation [?, ?], which may constrain the neural resources for high-acuity processing [?, ?]. Recent research [?, ?] found that compared to children, adults' VWFA-1 and FFA-1 have population receptive fields (pRFs) covering larger foveal visual field areas in the left and right hemispheres, respectively. Moreover, FG2 has higher NMDA receptor density than FG1 [?, ?]. These receptors are associated with learning, memory, and neural plasticity [?, ?], potentially making FG2 more suitable for the plasticity demands of literacy acquisition on face cortex. Second, although FG4 also preferentially encodes foveal stimuli [?, ?, ?], the lateralization competition between VWFA-2 and FFA-2 appears more influenced by lateralized connectivity with relevant brain networks. Layers IIIc in FG2 and FG4 contain medium and large pyramidal cells showing strong cortico-cortical connectivity characteristics, which may provide the structural basis for the interface between "bottom-up" and "top-down" processing [?, ?]. Importantly, layer V of FG4 can be subdivided into Va and Vb sublayers, whose functional significance remains unclear. However, layer V has the highest density of muscarinic M2 receptors [?, ?]. Muscarinic receptors can inhibit weak sensory input in layer IV and enhance input in layers II, III, and V, thereby improving cortical integration of sensory information [?, ?], which may explain why FG4 has stronger connectivity with other brain regions. Future research should further clarify the cellular types, lamination, density, synaptic connections, myelination, and receptor characteristics of FG2 and FG4 to provide a more solid functional neurohistological foundation for elucidating the competitive lateralization mechanism between words and faces.

Third, the lateralization competition mechanism between Chinese characters and faces. Unlike alphabetic scripts that compete with faces for neural processing resources in the left FG, the neural development of Chinese character recognition shows a different pattern of competition with face representation. ERPs and EEG gamma wave studies of preschool children (5-6 years) learning Chinese characters [?, ?, ?] found that the left-lateralized N170 amplitude evoked by Chinese characters negatively correlated with the right-lateralized N170 amplitude evoked by faces, indicating that early reading experience not only leads to left-hemisphere dominance for Chinese character recognition but also competes with face processing resources in the right hemisphere. Researchers speculate that words and faces have a competitive relationship in early development but a facilitative relationship in school-age children [?, ?, ?]. However, fMRI studies of preschool children (4-6 years) learning alphabetic scripts found that when children acquire letter knowledge, the left FG response to faces weakens [?, ?, ?], and as reading performance improves, right FG activity to faces significantly increases [?, ?, ?]. Thus, the pattern observed in preschool and school-age children learning alphabetic scripts is consistent: words and faces compete in the

left hemisphere, leading to left-lateralization of the VWFA and driving right-lateralization of the FFA. In essence, the "competitive relationship" reflects an intrinsic processing mechanism where words may occupy cortical space for faces, interfering with or reducing processing efficiency and causing face lateralization to weaken in one hemisphere. The "facilitative relationship" emphasizes that the left-lateralized VWFA resulting from word-face competition in the left hemisphere drives the right-lateralization of the FFA.

The different manifestation of competition between Chinese characters and faces in preschool children may be related to the more complex visual configuration features of Chinese characters compared to alphabetic scripts, requiring greater involvement of the right hemisphere, which excels at visuospatial discrimination [**?**, **?**, **?**]. Notably, Zhao et al. [**?**, **?**] found that visual discrimination training of Chinese characters in preschool children (4-6 years) induced larger N170 amplitudes in the right hemisphere for characters and smaller N170 amplitudes in the left hemisphere for faces. This suggests that the right hemisphere plays an important role in early Chinese character visual experience, but Chinese characters may also compete with faces for resources in the left hemisphere. It can be inferred that early Chinese character reading in preschool children depends on both right-hemisphere discrimination of character forms and left-hemisphere access to orthographic, phonological, and semantic information, so early reading experience may compete with face processing resources in both hemispheres. During school age, as reading proficiency increases, competition between Chinese characters and faces in the left hemisphere intensifies, accelerating left-lateralization of characters and driving right-lateralization of faces. Future studies should employ cross-sectional designs with preschool and school-age children, using high-temporal-resolution ERPs and high-spatial-resolution fMRI to systematically investigate the unique mechanisms by which early reading experience influences the lateralization competition between Chinese characters and faces.

Fourth, the developmental mechanism of right-lateralization for face recognition. Although evidence from children and adults tends to support that literacy acquisition drives the right-lateralized development of the FFA, illiterate adult adults also show some degree of right-hemisphere advantage [**?**, **?**], suggesting that literacy acquisition is only one factor influencing the right-lateralized development of face recognition [**?**, **?**]. Both word and face recognition lateralization are driven by learning and experience, but unlike literacy acquisition, which relies primarily on explicit, intensive instruction, individuals are automatically exposed to faces from early life [**?**, **?**]. The right-lateralization of face recognition shows a nonlinear developmental trajectory across the lifespan [**?**, **?**, **?**]. Right-hemisphere advantages for face recognition emerge in infancy [**?**, **?**, **?**, **?**, **?**], possibly because infant face recognition primarily relies on low spatial frequency visual information [**?**, **?**, **?**]. As the corpus callosum matures (from 3 months to 2 years) [**?**, **?**, **?**], particularly with myelination of the posterior portion facilitating interhemispheric visual information transfer [**?**, **?**], face recognition gradually relies on processing in both hemispheres. By preschool age (5-6 years), the

right-hemisphere advantage for face recognition gradually disappears [?, ?, ?]. However, with the onset of literacy acquisition, the right-hemisphere advantage for face recognition re-emerges and stabilizes in adulthood [?, ?]. Thus, the right-lateralized development of face recognition undergoes a substantial time delay, influenced not only by brain maturation and literacy acquisition but also by the slow accumulation of face experience. Research has found that as children and adolescents acquire skilled reading, face recognition ability and right FFA lateralization require considerable time to reach adult levels [?, ?, ?, ?]. For example, the volume of right FFA selective activation in children is about one-third that of adults [?, ?], and FFA-1 shows the greatest expansion during childhood and adolescence [?, ?]. Moreover, the size of right FFA volume in children (7-11 years) and adolescents (12-14 years) correlates significantly positively with face recognition memory ability, a relationship not observed in adults [?, ?]. Therefore, the development of right FFA lateralization may reflect changes in individuals' face recognition and perceptual experience. Recent research [?, ?] found that with children' s development, the increased selectivity of FFA-1 directly correlates with decreased selectivity of the occipitotemporal sulcus limbs area, suggesting that face recognition may reuse cortical space from limb areas in the right FG. Furthermore, like words, face perceptual experience may further adjust the function of different regions along the posterior-anterior computational axis in the right vOTC. For example, the peak activation of adult FFA is located in anterior regions, whereas the peak of selective FFA activation in children (5-8 years) is located in posterior regions, shifting anteriorly as children accumulate face experience [?, ?]. Additionally, right FFA-2 is more susceptible to modulation by face perceptual experience [?, ?] and is closely related to individuals' goals or needs in face recognition [?, ?]. Future research should therefore not only focus on how literacy acquisition competes with face representation for processing resources in the left FG but also investigate how face perceptual experience influences the right-lateralized development of the FFA and its cooperative representational relationships with other cortical areas.

[Figure 4: see original paper]

Fifth, the brain plasticity mechanisms of learning to read numbers and musical notation. Numbers and musical notation are also cultural inventions of humanity. Does learning to read them induce similar brain plasticity changes as literacy acquisition? Evidence suggests that the visual number form area (VNFA), which preferentially encodes Arabic numerals, is located lateral to the fusiform body area (FBA) but more lateral than the VWFA [?, ?], while the visual selectivity area for musical notation is located posterior-lateral to the VWFA [?, ?, ?]. This indicates that number and musical notation recognition occupy regions in the lateral FG adjacent to the VWFA, suggesting that their reading also depends on processing high-acuity visual signals from the fovea and shape-invariant perception [?, ?, ?, ?]. However, number reading requires mapping numerals onto quantity representations, causing the VNFA to compete not only with body-selective areas for resources but also to utilize the right intraparietal sulcus (IPS) and frontoparietal number regions for action and spatial representations

to parse abstract numerical information [?, ?, ?, ?]. Therefore, the VNFA shows strong lateralized connectivity with the right-hemisphere frontoparietal number processing network [?, ?, ?, ?], leading the VNFA to appear more lateral than the VWFA [?, ?] and to exhibit right-hemisphere advantage [?, ?, ?]. In contrast, musical notation reading requires greater utilization of neural connections from the FG to motor execution networks to complete visual-motor encoding transformations [?, ?, ?, ?]. Moreover, the musical notation recognition area shows stronger connectivity with the posterior lateral temporal region, causing it to appear posterior-lateral to the VWFA but with left-hemisphere advantage [?, ?]. Thus, reading acquisition for numbers, musical notation, and words shares fundamentally similar brain plasticity mechanisms: they all need to utilize cortical areas in the FG originally available for representing objects from other domains (e.g., objects, faces, or bodies) and form their unique cortical localization and different hemispheric lateralization effects through lateralized connectivity with relevant brain networks.

Future research should investigate the interrelationships among the brain plasticity changes induced by learning to read numbers, musical notation, and words. For example, although right VNFA shows stronger activation in number recognition, both split-brain patients and pure alexia patients can recognize Arabic numerals with both hemispheres, suggesting that the VNFA may be bilateral [?, ?]. Moreover, left VNFA shows stronger activation not only to letters but also overlaps substantially with the VWFA [?, ?], raising the question of whether left VNFA and VWFA emerge as a combined region or as two distinct areas [?, ?, ?]. Additionally, number reading requires not only activation of right VNFA, right IPS, and frontoparietal number areas but also involvement of left-hemisphere brain regions for number word phonological processing. Therefore, skilled number processing requires flexible switching between networks representing number shape, quantity, and number words, also known as the Triple Code Model (TCM) of numerical cognition [?, ?]. Future research should investigate the plastic changes in connectivity among these three networks during children' s number reading acquisition and their impact on the development of numerical operation or thinking abilities [?, ?, ?]. Furthermore, musical notation reading not only strengthens the structural and functional connectivity between the left musical notation recognition area and the perisylvian phonological network but also leads to expansion of the musical notation recognition area, while the VWFA shifts medially and anteriorly [?, ?, ?]. Thus, the brain plasticity mechanisms of musical notation and word reading not only share the same structural and functional connectivity target network in the left hemisphere but may also compete for cortical space between these two domains. However, current evidence comes from comparisons between adult musicians and non-musicians. Future research should employ longitudinal designs to compare children with different levels of word and musical notation reading ability, to examine how early experience with words and musical notation affects the competition for cortical space between the VWFA and musical notation recognition area, and how the localization and lateralization of these two brain regions are modulated top-down

by the perisylvian phonological network. In summary, the brain structural and functional networks for reading words, numbers, and musical notation are both segregated and overlapping, both competitive and cooperative. Importantly, children' s learning of these three visual symbols may occur synchronously or asynchronously in time. Therefore, investigating the temporal dynamics and neural mechanisms of the interactions among children' s word, number, and musical notation reading acquisition will not only have theoretical significance for deepening understanding of brain plasticity in cultural learning but also practical implications for guiding early instruction in language, mathematics, and music.

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Note: Figure translations are in progress. See original paper for figures.