

Competitive Developmental Mechanisms Underlying the Complementary Hemispheric Lateralization Patterns for Text and Face Recognition

Authors: Gao Fei, Cai Houde, Qi Xingliang, Cai Houde

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Abstract

In the adult brain, the left VWFA is more sensitive to orthographic information, while the right FFA preferentially processes facial information. However, the developmental mechanisms underlying this lateralized complementary pattern remain to be elucidated. The neuronal recycling hypothesis posits that during literacy acquisition, word recognition competes with face representations for neural processing resources in the left FG, leading to leftward lateralization of the VWFA for word recognition and driving rightward 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 parcellation 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. Based on the neuronal recycling hypothesis and the distributed hemispheric organization perspective, combined with the structural and functional characteristics of the FG and recent research evidence, this study systematically investigates the cognitive neural processing mechanisms underlying the competitive development of the hemispheric lateralized complementary pattern for word and face recognition. Future research should further investigate the cortical spatial locations 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 rightward lateralization for face recognition, and the mechanisms of brain plasticity changes induced by learning to read numbers and musical notes.

Full Text

Preamble

In adults, the left hemisphere's Visual Word Form Area (VWFA) exhibits greater sensitivity to orthographic information, while the right hemisphere's Fusiform Face Area (FFA) preferentially processes facial information. However, the developmental mechanisms underlying this complementary pattern of hemispheric lateralization remain to be fully 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-lateralization of the VWFA and driving right-lateralization of the FFA for face recognition. The distributed account of hemispheric organization proposes three key neural computational principles to systematically explain the multilevel, bidirectional dynamic processing mechanisms governing this competitive development of lateralization for words and faces. Recent advances in research on the structural parcellation and functional characteristics of the FG have yielded valuable new findings, enabling the construction of a multidimensional computational model of word and face recognition. By integrating the neuronal recycling hypothesis and distributed hemispheric organization perspective with the structural and functional features of the FG and recent empirical evidence, this paper systematically examines the cognitive and neural processing mechanisms underlying the competitive development of the complementary hemispheric lateralization pattern for word and face recognition. Future research should further investigate the cortical spatial locations and functional neurohistological basis of competitive processing between words and faces, the unique processing mechanisms of Chinese character-face competition, the developmental mechanisms of right-hemisphere specialization for face recognition, and the neural plasticity mechanisms underlying learning to read numbers and musical notation.

Keywords: visual word form area, fusiform face area, complementary pattern of hemispheric lateralization, competitive development mechanism, multilevel bidirectional dynamic processing

Both word and face recognition rely on expert visual processing to discriminate highly similar stimuli with subtle differences [?, ?]. Neuroimaging [?, ?, ?], electrophysiological [?, ?, ?], and neuropsychological studies [?, ?, ?] in adults demonstrate 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, whereas the right hemisphere's fusiform face area (FFA) preferentially processes facial information [?, ?, ?, ?, ?]. However, the developmental mechanisms underlying this mature complementary lateralization pattern remain to be clarified.

Notably, Dehaene and colleagues [?, ?, ?, ?, ?] proposed the neuronal recy-

clinging hypothesis to explain the hemispheric complementary lateralization of the VWFA and FFA. This hypothesis suggests that during literacy acquisition, word recognition may compete with face representation for neural processing resources in the left FG, resulting in left-lateralization of the VWFA and driving right-lateralization of the FFA. Subsequently, Behrmann and Plaut [?, ?, ?, ?] advanced the distributed account of hemispheric organization to systematically articulate the neural computational principles underlying the competitive development of lateralization for word and face recognition. Recent research on the structural parcellation and functional characteristics of the FG has yielded important new findings, providing the necessary neural structural and histological foundation for elucidating this competitive developmental mechanism. Therefore, further investigation of the cognitive and neural mechanisms underlying the competitive development of the complementary hemispheric lateralization pattern for word and face recognition, grounded in the neuronal recycling hypothesis and distributed hemispheric organization perspective and integrated with FG structural and functional features and recent empirical evidence, is not only crucial for revealing the brain plasticity mechanisms underlying the developmental relationship between word and face processing but also valuable for guiding literacy instruction, artificial intelligence simulation of word and face recognition, and clinical practice.

Accordingly, this paper first introduces the neuronal recycling hypothesis and related evidence, demonstrating that competitive processing between literacy acquisition and face representation in the left FG may lead to the complementary lateralization pattern for word and face recognition. It then elaborates on the three neural computational principles of word and face recognition, showing that this lateralized competition is a bidirectional dynamic process occurring across multiple hierarchical levels of the vOTC. Subsequently, we present the structural parcellation and functional characteristics of the FG and, based on the multidimensional computational model comprising medial-lateral and posterior-anterior computational axes, preliminarily clarify the cognitive and neural mechanisms underlying the multilevel, bidirectional dynamic processing of competitive lateralized development of the VWFA and FFA. Finally, we outline several important directions for future research.

2. The Neuronal Recycling Hypothesis of Literacy Acquisition and Related Evidence

Writing represents one of humanity's most important cultural inventions. Written works first appeared approximately 5,400 years ago in Babylon [?, ?], and until about 200 years ago, literacy remained confined to a small segment of the population [?, ?]. Dehaene and colleagues [?, ?, ?, ?] argue that the brain has not had sufficient time to evolve specialized neural systems for reading; instead, literacy requires repurposing or recycling cortical regions originally responsible for more ancient functions without any genetic reorganization, instead leveraging brain plasticity. This theory is known as the neuronal recycling hypothesis

[?, ?]. The vOTC serves as a convergence zone specialized for recognizing visual stimuli from different domains, including faces, locations, bodies, and objects [?, ?]. Because face-selective regions require longer developmental periods and continue to exhibit structural and functional changes until adulthood, they are more plastic than regions selective for other stimuli (such as locations) [?, ?]. 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, thereby producing left-lateralization of the VWFA, while face recognition gradually shifts to the right FG, resulting in right-lateralization of the FFA [?, ?].

Numerous lines of evidence support 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 as children acquire letter knowledge, the left FG's response to letters strengthens while its response to faces diminishes [?, ?, ?], and with improved reading performance, neural activity in the right FG to faces increases significantly [?, ?, ?]. Behavioral and event-related potential (ERP) studies further demonstrate that children exhibit a right visual field-left hemisphere advantage for word processing even in the early stages of reading acquisition, whereas the left visual field-right hemisphere advantage for face processing is not pronounced in children and adolescents but correlates positively with reading comprehension ability [?, ?]. Additionally, the amplitude of left-lateralized N170 evoked by words correlates positively with right-lateralized N170 evoked by faces in 7- to 11-year-old children [?, ?]. These findings suggest that hemispheric lateralization for word and face recognition may develop jointly.

Second, literacy acquisition in adulthood induces hemispheric lateralization changes similar to those observed during childhood. Dehaene et al. [?, ?] conducted fMRI studies comparing illiterate adults, ex-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 strong activation to faces; as literacy improved from ex-illiterates to skilled readers, the left VWFA's response to faces decreased while the right FFA's response to faces increased. Pegado et al. [?, ?] further demonstrated using ERPs that as reading ability improved from illiterate adults to ex-illiterates to skilled readers, the left-lateralization of N170 evoked by letter strings strengthened, while the right-lateralization of N170 evoked by faces intensified.

Third, language lateralization in left-handers determines the developmental trajectory of face lateralization. Dundas et al. [?, ?] found that in right-handers, the amplitude of N170 evoked by words in the left hemisphere correlated positively with 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 advantage [?, ?, ?]. Because

words fail to exert sufficient pressure on face processing in the left visual cortex, left-handers tend to show bilateral FFA activation for faces [?, ?]. Gerrits et al. [?, ?] further distinguished left-handers with right- versus left-hemisphere language dominance using fMRI, revealing opposite lateralization patterns: the former showed right-lateralized word processing and left-lateralized face processing, while the latter showed the reverse pattern. These findings indicate that when left-handers exhibit 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 can affect hemispheric competition between words and faces. ERP studies of developmental dyslexia (DD) and developmental prosopagnosia (DP) [?, ?] revealed that individuals with DD showed no lateralized advantage for N170 responses to either words or faces, whereas individuals with DP exhibited left-lateralized N170 only for words. One possible explanation is that DD impairs word recognition ability, eliminating the competitive pressure from words in the left hemisphere that would normally drive right-lateralization of face representation, resulting in the absence of hemispheric advantage for both domains. In contrast, DP's face recognition deficit only impedes right-lateralization of face representation without compromising the left-lateralized development of word recognition. A three-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) following surgery at age 6 years 9 months, only the VWFA was detected in the left vOTC, whereas by the fourth scan (age 10 years 10 months), both VWFA and FFA were present in the left vOTC. Compared to control subjects, U.D.'s VWFA was located significantly more laterally, while the FFA's activation magnitude and extent increased with age and was positioned more medially than normal [?, ?]. These findings demonstrate that when face representation must recycle left FG cortex, it similarly competes with words for neural processing resources.

Collectively, these lines of evidence converge to suggest that literacy acquisition may compete with face representation for neural processing resources in the left FG, triggering 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 the interpretation of competitive processing mechanisms based on correlations between VWFA and FFA activity is largely speculative. Therefore, it is necessary to investigate the detailed processing mechanisms underlying this competitive lateralization between these two brain regions.

3. The Distributed Account of Hemispheric Organization

Behrmann and Plaut [?, ?, ?, ?] propose that the hemispheric organization of word and face recognition follows three key neural computational principles: (1)

multilevel distribution of representations and knowledge, (2) coexistence of competition and cooperation among representations, and (3) spatial localization of brain regions. First, representations of words and faces are distributed across hierarchical levels from the primary visual cortex (V1), which processes local retinal information, to the anterior temporal cortex, which 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 representational formats but may also recruit additional neurons and brain regions to refine and specialize representations [?, ?]. Second, although words and faces belong to different visual domains, their recognition both depend on high-acuity vision [?, ?, ?] and extensive learning [?, ?]. On one hand, both types of representation must cooperate with central visual information representation, causing them to compete for neural spatial resources in adjacent regions that encode foveal retinal information projection cortex [?, ?, ?, ?]. On the other hand, because the systematicity or consistency of feature-related knowledge representations differs markedly between the two domains at various hierarchical levels, a cortical region that represents face information becomes unsuitable for representing word information, ultimately leading to word and face knowledge being represented by distinct cortical regions [?, ?]. Third, during evolution, brain organization requires sufficient neuronal connections to support necessary information processing, yet the total volume of axonal fibers is constrained by cranial volume. Therefore, spatial localization achieved through minimization of axonal length not only reduces axonal volume but also prevents unnecessary errors resulting from increased signal transmission distances. Consequently, on the cortical map, adjacent cortical regions are more likely to develop cooperative representational relationships, whereas regions with competitive representational relationships maintain some distance from each other. Thus, to minimize synaptic connection length, the cortical region representing orthographic words may be constrained to the hemisphere adjacent to language-related (particularly phonological) processing regions. Since language representation is left-lateralized in most individuals and shares colateralization with the word processing network [?, ?, ?], word representation tends to be left-lateralized. Finally, as reading experience increases, the left vOTC (VWFA) becomes increasingly specialized for representing word information [?, ?], intensifying competition between words and faces in this region and causing bilateral face representation in preschool children to become increasingly dependent on the right vOTC (FFA) with literacy acquisition [?, ?, ?].

The distributed account thus suggests that competitive lateralized processing of words and faces is a bidirectional dynamic process occurring across multiple hierarchical structures in the hemispheric vOTC, constrained by bottom-up sensory input from V1 and modulated by top-down information processing from higher cortical regions (such as language areas). At lower processing levels, word and face recognition share bottom-up high-acuity visual information, lead-

ing to competition for early perceptual cortical spatial resources and initiating the emergence of left-lateralized VWFA and right-lateralized FFA. At higher processing levels, this early competition is modulated by top-down information processing driven by learning and experience, fostering the development of lateralization for word and face recognition. Notably, recent advances in research on FG structural parcellation and functional characteristics have provided important insights that may clarify the cognitive and neural mechanisms of this multilevel, bidirectional dynamic processing. The following sections systematically examine the relationship between FG structure and function and the competitive lateralized development of the VWFA and FFA.

4.1 Four Structural and Functional Regions of the FG

The FG is a crucial structure in the vOTC connecting the ventral occipital cortex (VOC) and ventral temporal cortex (VTC), bounded laterally by the occipitotemporal sulcus (OTS), medially by the collateral sulcus (CoS), posteriorly by the posterior transverse collateral sulcus (ptCoS), and anteriorly by the anterior tip of the mid-fusiform sulcus (MFS) [?, ?, ?, ?, ?, ?] [Figure 1: see original paper]. Research indicates that the MFS longitudinally divides the FG into distinct medial-lateral structural and functional regions that align with, overlap, or are nested within the MFS [?, ?] [Figure 1: see original paper].

Specifically, FG1, located medially and extending toward the CoS, is adjacent to the human occipital cortex 4 ventral (hOc4v), while FG2 is located laterally and extends toward the OTS [?, ?] [Figure 1: see original paper]. Functionally, FG1 serves as a transitional area between early visual cortex (V1, V2/V3, and V4) and higher-level visual cortex (VTC), whereas FG2 functions as an associative region of visual cortex [?, ?, ?] responsible for preliminary perceptual integration of stimuli [?, ?]. Cytoarchitectonic and receptor mapping studies have further identified FG3 and FG4 in the mid-anterior FG, distinguished by the MFS [FIGURE:1, 2]. FG3, located anterior to FG1, contains the collateral sulcus place-selective area (CoS-places) [?, ?, ?, ?], while FG4, located anterior to FG2, primarily processes object identity and meaning [?, ?, ?, ?].

Critically, based on the structural parcellation 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 represents a domain-specific computational axis that physically segregates processing regions for different domains, enabling efficient parallel processing of domain-specific information. The posterior-anterior axis represents a computational axis of hierarchical transformation within domains, implementing a series of hierarchical computations across posterior-to-anterior cortex to achieve behaviorally relevant representations [?, ?, ?, ?]. In this model, word and face recognition areas are distributed in the lateral FG regions FG2 and FG4, which preferentially process foveal visual input and are suited for high-acuity visual processing and fine-grained discrimination. Specifically, FFA-1 and VWFA-1 in FG2 are dis-

tributed in a medial-lateral overlapping pattern, while FFA-2 and VWFA-2 in FG4 are also medial-laterally distributed but separated by the fusiform body area (FBA) [Figure 2: see original paper]. According to this model, visual information for faces and words undergoes preliminary processing of perceptual features in early visual cortex before entering FG2 via FG1, then transmitting from FFA-1 and VWFA-1 to FFA-2 and VWFA-2, respectively, to complete 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 both the medial-lateral and posterior-anterior axes of the FG.

It should be noted that the FG's multidimensional computational model does not explain how this dynamic processing is modulated by bottom-up and top-down information processing, nor does it address its relationship to the hemispheric competitive lateralization of the VWFA and FFA. Based on the partitioning characteristics shown in [Figure 2: see original paper], VWFA-1 and FFA-1 in FG2 occupy lower levels of the posterior-anterior axis with some cortical spatial overlap (low domain specificity), suggesting that their processing is primarily constrained by bottom-up sensory input. Therefore, FG2 may be the cortical site where early competition between words and faces emerges. In contrast, VWFA-2 and FFA-2 in FG4 occupy higher levels of the posterior-anterior axis with spatially segregated cortical territories (high domain specificity), suggesting that their processing occurs later in perception and is primarily modulated by top-down information processing through learning and experience, potentially leading to stronger hemispheric lateralization of these two regions. The following sections review relevant evidence and explore this mechanism.

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

FG2 receives early visual cortical information transmitted from FG1 and performs perceptual representation based on shape invariance 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 their activation zones overlapping in areas near the foveal projection cortex [?, ?, ?]. Importantly, FG1 exhibits strong co-activation with early visual cortex and relatively symmetric interhemispheric function [?, ?], whereas FG2 begins to show some degree of functional asymmetry for words and faces, with words eliciting co-activation of left FG2 with reading-related brain regions and faces eliciting co-activation of right FG2 with face-processing-related regions [?, ?, ?]. VWFA-1 is localized in left FG2, while FFA-1 appears more frequently in right FG2 [?, ?]. Thus, word and face recognition share fine-grained visual input from the fovea in FG2 [?, ?, ?], causing literacy acquisition to compete with face representation for early perceptual cortical spatial

resources [?, ?, ?, ?], which drives FG2 to begin differentiating distinct hemispheric lateralization representation systems for word and face recognition [?, ?].

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, so the early competition-driven left-lateralization of VWFA-1 and right-lateralization of FFA-1 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 also undergo top-down modulation through connectivity with relevant brain networks driven by learning and experience. Connectivity refers to the degree of information exchange between cortical regions, including both 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 fronto-temporal 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 emotion processing (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 increases, not only does the lateralized connectivity between VWFA-2 and relevant brain networks strengthen, but its selective response to words also becomes more robust [?, ?, ?]. For example, literacy acquisition leads to significantly increased fractional anisotropy (FA) in the posterior left 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 inferior frontal cortex and left planum temporale during spoken word processing [?, ?]. Moreover, 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 during literacy acquisition [?, ?, ?]. Similarly, face recognition ability correlates positively with FA values in the right ILF connecting to FFA-2 [?, ?], while congenital prosopagnosia patients show compromised integrity in the right ILF and IFOF, with FA values correlating negatively with face recognition error rates only in the right hemisphere [?, ?], indicating that the right ILF and IFOF may be two critical pathways for integrating holistic structural face information with emotion and memory representations [?, ?]. Notably, these lateralized connections are pre-existing in the brain, and learning experience with words or faces can shape word- or face-selective regions by altering connectivity in relevant brain networks, thereby predicting their cortical locations in children or adult individuals [?, ?, ?]. In

summary, literacy experience can enhance the connectivity between VWFA-2 and left-lateralized language networks, thereby strengthening competitive processing between words and faces in the left hemisphere, accelerating the establishment of left-lateralized word recognition, and promoting the development of right FFA-2. Concurrently, accumulated face experience strengthens the right-lateralized connectivity of FFA-2 with relevant brain networks, leading to progressively stronger right-lateralization of face recognition. This learning- and experience-driven processing occurs primarily in later stages of word or face perception and influences competitive hemispheric lateralization development in a top-down manner.

5. Summary and Outlook

Over the past 10–20 years, research on the complementary hemispheric lateralization pattern and its developmental mechanisms in word and face recognition 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 right-lateralized FFA—the precise cortical competitive processing mechanisms underlying this lateralization have only recently become clear. On one hand, the lateralized competition between word recognition and face representation is a bidirectional dynamic process occurring across multiple hierarchical structures of the vOTC. On the other hand, the four FG structural and functional regions distinguished based on the MFS, and the resulting multidimensional computational model, provide a framework for elucidating the bidirectional competitive processing mechanisms underlying the complementary lateralized development of the VWFA and FFA. Integrating existing theoretical models and empirical evidence, this paper presents a schematic diagram illustrating the multilevel, bidirectional dynamic processing mechanism of competitive development in 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 (lateral to the medial-lateral axis) in the left hemisphere and FFA-1 (medial to the medial-lateral axis) in the right hemisphere. As literacy and face recognition experience accumulate, processing of word or face information transitions from VWFA-1 and FFA-1 in FG2 to VWFA-2 (lateral to the medial-lateral axis) and FFA-2 (medial to the medial-lateral axis) in FG4 in the mid-anterior lateral FG. Because literacy acquisition strengthens the connectivity between VWFA-2 and left-hemisphere language networks, this top-down lateralized modulation intensifies competitive processing between words and faces, resulting in stronger left-lateralization of VWFA-2 and accelerated right-lateralization of FFA-2. Simultaneously, face learning experience enhances 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 hemispheric lateralization pattern for word and face recognition is a bidirectional dynamic process occurring across multiple dimensions of the FG.

Although the competitive development mechanism of this complementary lateralization pattern has been preliminarily elucidated, several critical issues and directions require further investigation.

First, the cortical spatial mechanisms of competitive processing between words and faces require clarification. Much of the evidence supporting the neuronal recycling hypothesis derives from 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 to different categories to appear overlapping when they may actually occupy distinct, well-defined territories in different individuals [?, ?]. Therefore, longitudinal evidence from the same group of children at different ages during literacy acquisition is needed to track changes in activation levels across 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 in the left hemisphere but observing that right FFA activation increased with reading scores. Importantly, during this process, the VWFA encroached upon neuronal patches near face representation regions that showed weak and unstable responses to tools [?, ?]. Based on these findings, 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 increases, which blocks the expansion of object- or face-responsive patches and gradually shifts face representation to the right FG. To further examine the effects of brain maturation and reading level on this effect, Feng et al. [?, ?] conducted fMRI scans in preliterate 6-year-olds, 6-year-olds beginning reading instruction, and skilled-reading 9-year-olds, supporting this blocking model: literacy acquisition does not directly compete with faces but instead indirectly blocks the slow development of face representation in the left hemisphere, thereby enhancing right-lateralization of faces. These results better explain the marginal competition effect reported by Dehaene et al. [?, ?], where although FFA peak activation was unaffected by reading ability, competitive effects were observed in voxels 12 or 16 mm from the FFA peak, with left FFA activation decreasing as reading scores improved. Future studies should employ high-resolution (<1 mm) fMRI techniques [?, ?, ?] to examine competitive effects in 1-mm voxels radiating from the FFA peak center 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 lateralized competitive processing between words and faces requires deeper investigation. Although evidence

indicates that both FG2 and FG4 are involved in word and face recognition, the functional neurohistology of how these regions participate in competitive processing remains unclear. First, the high density of large pyramidal cells in FG2 may be related to high-acuity foveal computation [?, ?], which may constitute the neural resource constraint on high-acuity processing [?, ?]. Recent research [?, ?] found that compared to children, adults' VWFA-1 and FFA-1 have smaller population receptive fields (pRFs) and higher foveal bias, suggesting that the development of word and face recognition may involve pRF changes in FG2. However, the functional neurohistological basis of this developmental change remains unknown. Second, although FG4 also preferentially encodes foveal stimuli [?, ?, ?, ?], the lateralized 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 connection characteristics, which may provide the structural basis for the interface between bottom-up and top-down processing [?, ?]. Importantly, layer V in FG4 can be subdivided into Va and Vb sublayers, whose functional significance remains unclear. However, layer V shows the highest density of muscarinic M2 receptors [?, ?], which can inhibit weak sensory input to layer IV and enhance input to layers II, III, and V, thereby improving cortical integration of sensory information [?, ?], perhaps explaining FG4's stronger connectivity with other brain regions. Future research must further characterize the cellular types, laminar organization, density, synaptic connections, myelination, and receptor profiles of FG2 and FG4 to provide a more solid functional neurohistological foundation for understanding the competitive lateralization mechanism.

Third, the competitive lateralization mechanism between Chinese characters and faces requires investigation. Unlike alphabetic scripts, which compete with faces for neural processing resources in the left FG, Chinese character recognition shows a different pattern of neural development in competition with face representation. ERP and EEG gamma wave studies in preschool children (5–6 years) learning Chinese characters [?, ?, ?] found that the amplitude of left-lateralized N170 evoked by Chinese characters correlated negatively with right-lateralized N170 evoked by faces, indicating that early reading experience in children leads not only to left-hemisphere advantage for Chinese character recognition but also to competition with face processing in the right hemisphere. The researchers speculated that during early development, words and faces have a competitive relationship, whereas in school-age children they have a facilitative relationship [?, ?, ?]. However, fMRI studies in preschool children (4–6 years) learning alphabetic scripts found that as children acquired letter knowledge, the left FG's response to faces decreased [?, ?, ?], and with improved reading performance, neural activity in the right FG to faces increased significantly [?, ?, ?]. Thus, the pattern induced by alphabetic script learning in preschool and school-age children is consistent: words and faces compete in the left hemisphere, leading to left-lateralized VWFA and driving right-lateralized FFA. In essence, the “competitive relationship” reflects an intrinsic processing mechanism whereby

words may occupy cortical spatial resources for faces, thereby interfering with or reducing processing efficiency and causing weakened face lateralization in one hemisphere. The “facilitative relationship” emphasizes that left-lateralized VWFA resulting from word-face competition in the left hemisphere drives right-lateralization of the FFA. The competition between Chinese characters and faces in the right hemisphere during preschool may be related to the more complex visual configuration 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) elicited larger N170 amplitudes in the right hemisphere, while N170 amplitudes evoked by faces in the left hemisphere decreased, suggesting 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 speculated that Chinese character learning in preschool children depends on both right-hemisphere discrimination of visual form and left-hemisphere access to orthographic, phonological, and semantic information, such that early reading experience may compete with face processing 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 words and driving right-lateralization of faces. Future research should employ cross-sectional longitudinal designs with preschool and school-age children, using high-temporal-resolution ERP and high-spatial-resolution fMRI techniques to systematically investigate the unique mechanisms by which early reading experience influences the competitive lateralization between Chinese characters and faces.

Fourth, the developmental mechanism of right-hemisphere specialization for face recognition requires further investigation. Although evidence from children and adults tends to support the notion that literacy acquisition drives the right-lateralized development of the FFA, illiterate adults also show some degree of right-hemisphere advantage [?, ?], suggesting that literacy is only one factor influencing the development of right-lateralized face recognition [?, ?]. Both word and face recognition lateralization are driven by learning and experience, but unlike literacy acquisition, which relies primarily on explicit instruction, individuals are automatically exposed to faces from early life [?, ?]. The right-lateralization of face recognition follows a nonlinear developmental trajectory [?, ?, ?]. Right-hemisphere advantage for face recognition emerges in infancy [?, ?, ?, ?, ?], possibly because infant face recognition relies mainly on low spatial frequency visual information [?, ?, ?]. As the corpus callosum matures (from 3 months to 2 years) [?, ?, ?], particularly with myelination of posterior regions promoting interhemispheric visual information transfer [?, ?], face recognition gradually becomes dependent on processing in both hemispheres. By the preschool period (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 development of right-lateralized face recognition involves a prolonged time course, influenced not only by brain maturation and literacy acquisition but also by the slow accumulation of face experience. Research shows that as children and adolescents acquire skilled reading, face recognition ability and FFA right-lateralization require considerable time to reach adult levels [?, ?, ?, ?]. For example, the volume of face-selective activation in the right FFA in children is approximately one-third that of adults [?, ?], and FFA-1 shows the greatest expansion during childhood and adolescence [?, ?]. Moreover, the size of the right FFA 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-lateralized FFA may reflect changes in individuals' face recognition and perceptual experience. Recent research [?, ?] found that as children develop, increased selectivity of FFA-1 directly correlates with decreased selectivity of the occipitotemporal sulcus limbs area (OTS-limbs), suggesting that face representation may recycle cortical space in the right FG originally used for limb representation. Furthermore, similar to words, face perceptual experience may further adjust the function of different regions along the posterior-anterior computational axis in the right vOTC. For instance, the peak activation of the adult FFA is located in anterior regions, whereas in children (5–8 years), the peak of face-selective activation 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 the purpose or need for individual face recognition [?, ?]. Future research should therefore investigate not only how literacy acquisition competes with face representation for neural processing resources in the left FG but also how face perceptual experience influences the right-lateralized development of the FFA and its competitive mechanisms for cortical space with other cortical regions.

In summary, although competition between words and faces in the left FG plays a crucial role in the development of the complementary hemispheric lateralization pattern for word and face recognition [Figure 3: see original paper], this mechanism typically occurs when school-age children begin learning to read, whereas face recognition lateralization undergoes changes from infancy through preschool, school age, and adulthood. [Figure 4: see original paper] presents the developmental time course of dynamic changes in hemispheric lateralization for word and face recognition. In infancy, face recognition shows right-hemisphere advantage; during the preschool period, face recognition becomes bilateral; in the school-age period, literacy acquisition leads to the development of the VWFA in the left FG, and the left FFA, blocked by the VWFA, gradually shifts its development to the right FG; in adulthood, the right-hemisphere advantage for face recognition reaches a mature and stable state.

Fifth, the brain plasticity mechanisms underlying learning to read numbers and musical notation require investigation. Numbers and musical notation are also human cultural inventions, and learning to read them may induce brain plastic-

ity changes similar to those observed in literacy acquisition. Evidence indicates 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 area of visual selectivity for musical notation is located posterior-lateral to the VWFA [?, ?, ?]. This suggests that number and musical notation recognition occupy lateral FG regions adjacent to the VWFA, indicating that their learning also depends on processing high-acuity foveal visual signals and shape-invariant perception [?, ?, ?, ?]. However, number reading requires mapping numerals onto quantity representations, causing the VNFA to compete not only with body representation areas but also to utilize the right intraparietal sulcus (IPS) and frontoparietal number regions for action and spatial representations to parse abstract numerical information [?, ?, ?, ?]. Consequently, the VNFA shows strong lateralized connectivity with right-hemisphere frontoparietal number processing networks [?, ?, ?, ?], leading the VNFA to appear more lateral than the VWFA [?, ?] and exhibit right-hemisphere advantage [?, ?, ?]. In contrast, musical notation reading requires greater utilization of neural connections from the FG to motor execution networks to accomplish visuomotor encoding transformations [?, ?, ?, ?]. Moreover, the musical notation recognition area shows stronger connectivity with the left posterior lateral temporal lobe, leading it to appear posterior-lateral to the VWFA but exhibit left-hemisphere advantage [?, ?]. Thus, reading acquisition for numbers, musical notation, and words shares fundamentally similar brain plasticity mechanisms: they all require recycling cortical regions in the FG originally available for representing objects from other domains (such as objects, faces, or bodies) and forming 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 activation is stronger during number recognition, both hemispheres can recognize Arabic numerals in split-brain and pure alexia patients, suggesting that the VNFA may be bilateral [?, ?]. Moreover, left VNFA not only shows strong activation to letters but also overlaps substantially with the VWFA [?, ?]. Therefore, whether left VNFA and VWFA emerge as a combined region or as two distinct regions remains to be determined [?, ?, ?]. Additionally, number reading requires not only activation of right VNFA, right IPS, and frontoparietal number regions but also involvement of left-hemisphere regions for number word phonological processing. Thus, skilled number processing requires flexible conversion among brain networks representing number shape, quantity, and number words, a framework known as the Triple Code Model (TCM) [?, ?]. 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 structural and functional connectivity between left musical notation recogni-

tion areas and perisylvian phonological networks but also leads to expansion of the musical notation recognition area and medial-anterior shift of the VWFA [?, ?, ?]. Therefore, the brain plasticity mechanisms underlying musical notation and word reading not only share the same target network of structural and functional connectivity in the left hemisphere but may also cause positional shifts in the VWFA due to cortical space competition between these two domains [?, ?, ?, ?]. However, current evidence comes from comparisons between adult musicians and non-musicians. Future studies should adopt longitudinal designs comparing children with different levels of word and musical notation reading ability to examine how early experience with word and musical notation reading affects competition for cortical space between the VWFA and musical notation recognition area and how the localization and lateralization of these two 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, competitive and coordinated. 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 interactions among word, number, and musical notation reading acquisition in children will not only deepen theoretical understanding of cultural learning brain plasticity but also have practical implications for guiding early instruction in language, mathematics, and music.

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