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The influence of orthographic depth on reading networks in simultaneous biliterate children

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ABSTRACT

Children in bilingual societies often simultaneously acquire reading skills in distinct writing systems that vary in consistency of sound–letter mapping or orthographic depth. To investigate its effect on cortical reading networks in children, we performed functional imaging on 34 simultaneous Hindi–English biliterate children as they read word and nonword stimuli. In contrast to Hindi which is consistent and relies on phonological assembly for both stimuli, English is inconsistent which necessitates lexical retrieval for words, but phonological assembly for nonwords. While children recruited a shared reading network for both languages, factorial analysis revealed stimulus effects (word/nonword) in bilateral frontal, parietal and left angular regions. Subsequent analyses showed that the stimulus effect was significant in English, which has a deep orthography, in comparison to Hindi, which is transparent. Our results provide novel evidence that orthographic depth shapes cortical reading processes during development.

1. Introduction

About two-thirds of the world's children grow up in bilingual environment (Bhatia & Ritchie, 2012; Crystal, 2003). In many such environments, children are instructed simultaneously in two languages (Bialystok, Luk, & Kwan, 2005) and are often biliterate in that they learn to read languages that belong to distinct writing systems. The writing system that a language uses affects children's acquisition of literacy because writing systems vary in their consistency in mapping of sounds onto units of print (Ziegler & Goswami, 2005) also known as orthographic depth (Katz & Frost, 1992). Based on this feature, transparent languages like Spanish with near univalent spelling-to-sound mapping occupy one end of a continuum and opaque orthographies such as English fall on the other end (Seymour, Aro, & Erskine, 2003).

Consequently, neuroimaging studies have shown that writing systems differing in orthographic depth vary in their cognitive demands (Bolger, Perfetti, & Schneider, 2005; Paulesu et al., 2000). Adult monoliterate readers of transparent writing systems like Spanish and Italian show primary reliance on phonological assembly (Carreiras, Mechelli, Estévez, & Price, 2007; Paulesu et al., 2000). On the other hand, monoliterate readers of English, an opaque writing system, show comparatively higher dependence on lexical processes (Paulesu et al., 2000) and show distinct reading strategies – lexical recall for words and phonological assembly for nonwords (Jobard, Crivello, & Tzourio-Mazoyer, 2003). Interestingly, similar orthographic depth effects have also been observed in adult Japanese monolinguals who read two writing systems – morphographic Kanji and syllabographic Hiragana (Buchweitz, Mason, Hasegawa, & Just, 2009; Duncan et al., 2013; Ha Duy Thuy et al., 2004; Iwata, 1984; Sakurai et al., 2000). More recently, such cross-linguistic differences in reading networks reflecting variation in orthographic depth has also been demonstrated in adult Spanish–English (Jamal, Piche, Napoliello, Perfetti, & Eden, 2012) and Hindi–English (Das, Padakannaya, Pugh, & Singh, 2011) bilinguals. Spanish–English bilinguals demonstrated involvement of semantic processing through left middle temporal gyrus while reading Spanish, and activation in frontal regions for English, indicating increased phonological processing demands. Similarly, evidence from adult Hindi–English biliterates also illustrated orthography-dependent reading strategies. Reading low frequency words in the transparent orthography – Hindi, was executed by dorsal route via inferior parietal lobule implicated in phonological processing whereas reading low frequency English words was accomplished via the inferior temporal region involved in lexical recall.

As evident from the aforementioned studies, biliteracy has been well-studied in adults (Chee, Tan, & Thiel, 1999; Das et al., 2011; Liu, Dunlap, Fiez, & Perfetti, 2007; Tan et al., 2003), but very little is known about how orthographic depth shapes reading networks in biliterate children. Initial evidence from neuroimaging in biliterate children has shown overlapping cortical circuits for reading native and second language, leading to the conjecture that a

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common network may be responsible for processing both languages. For instance, a study on semantic processing in sequential Chinese–English biliterate children demonstrated similar activation patterns for processing both languages (Xue, Dong, Jin, Zhang, & Wang, 2004). However, a recent study on Chinese–English biliterate children demonstrated activity in the left hemisphere caudate–fusiform circuit as a predictor of literacy skills in English (Tan et al., 2011), but not in Chinese. Similarly, a recent fNIRS study on Japanese–English children performing word repetition tasks also revealed cross-linguistic differences (Sugiura et al., 2011), which were attributed to differences in familiarity of phonology. Despite evidence from biliterate adult populations that supports influence of orthographic depth on reading networks, it has not been systematically investigated in children. In this paper, we focus on the role of orthographic depth on organisation of reading pathways in biliterate children provided simultaneous instruction in distinct writing systems.

Simultaneous reading instruction in native and second language is becoming an increasingly common feature of language learning environments across the globe, wherein reading acquisition in non-native language parallels language learning itself (Ranguelov, De Coster, Norani, & Paolini, 2012; Saiegh-Haddad & Geva, 2010; Silver, Hu, & Iino, 2002; Wang, 2007). This scenario opens up an exciting avenue to investigate neuroplasticity of the developing brain. The urban education environment in India is a natural setting admirably suited to explore this owing to its multilingual home environments and its education policy which requires children to learn more than one language at school (Annamalai, 2001).

The participants in our study were provided simultaneous reading instruction in Hindi and English, languages with distinct writing systems. Hindi, written in *Devanagari* script has a near transparent orthography with almost univalent mapping of sounds onto the basic written units, also called *Aksharas*. *Devanagari* is an alphasyllabary with distinct consonants and vowels akin to alphabetic scripts, but each grapheme corresponds to a syllable similar to syllabic scripts (Vaid & Gupta, 2002). On the other hand, English is alphabetic and has an opaque orthography which necessitates recruitment of whole-word processes for reading familiar stimuli, like words and assembly of phonological units for novel stimuli (Jobard et al., 2003). Conversely, the transparent nature of Devanagari allows the usage of phonological assembly for reading both novel and familiar stimuli (Das et al., 2011; Rao, Vaid, Srinivasan, & Chen, 2011). However, both English and Devanagari (Nag, Caravolas, & Snowling, 2011) represent phoneme level information, making it central to reading both languages as per the psycholinguistic grain size theory (Ziegler & Goswami, 2005) of reading acquisition. The primary focus of this study was to investigate whether this cross-linguistic variation in orthographic depth impacts reading pathways in biliterate children.

We used functional neuroimaging to measure brain activity during word and nonword reading tasks to investigate neural reading circuits in Hindi–English biliterate children. Based on literature on biliteracy and reports from adult simultaneous Hindi–English readers, we hypothesized that Hindi–English biliterate children would exhibit (1) overlap in reading pathways for reading Hindi and English (2) word and non-word processing strategies in the two languages which reflect disparity in orthographic depth.

2. Materials and methods

2.1. Participants

A detailed procedure was adopted to select participants for the study with similar language background. Forty-four typically developing, right handed, Hindi–English biliterate children (23 males) (mean age – 9.21 years, SD = 0.69) from a private school in National Capital Region, Delhi in northern India participated in the study which was approved by the Human Ethics Committee of the Institute. The recruitment of participants from a single school ensured matched instruction and reduced variability in the literacy environment. The native language for all participants was Hindi, while English was acquired primarily through schooling. At school, children simultaneously learnt to read both Hindi and English (from 5 years onwards), with the latter being the medium of instruction and within-classroom communication. All participants belonged to middle income families and as per the parental questionnaire, the education of parents was of graduate level and home environment typically involved usage of Hindi as well as English. All except one participant reported exposure to only English and Hindi and knew no other dialects/languages. All participants met our cut-off score on age appropriate reading tests developed in both languages (see Section 3.1) and had no history of reading difficulty as per school and parental reports.

The final study sample consisted of 34 participants (16 males) after discarding data from participants with excessive head motion and below average IQ score (as per assessment norms of Wechsler's Abbreviated Scale of Intelligence (WASI) (Wechsler, 1999) by a clinical psychologist). None of the participants had any history of sensory or neurological deficits, had normal or corrected to normal vision and normal intelligence (mean IQ = 104.81, SD = 7.94).

2.2. Language assessments

The participants were tested on a battery of behavioural tests in a separate session to assess reading ability and language skills in both Hindi and English (See Table 1). Five participants could not take part in the language assessment session and hence all measures were calculated for 29 participants. Reading assessment tested their reading ability on a subset of 20 words and 20 nonwords in each language, from the stimuli used for the fMRI reading task. To avoid confounding effects due to memory, all behavioural assessments were carried out between 4 and 6 weeks from the imaging session. Reading accuracy was determined from the reading tests for both languages. To determine reading accuracy, all responses for a stimulus which adhered to letter-to-sound correspondence rules were considered correct. For example, both /weɪpər/ and /wæpər/ were considered as correct responses to the nonword '*Waper*'.

Language assessments included rapid naming test, rhyme and spoonerism tests, and semantic fluency and alliteration tests. The phonological awareness test battery used for testing in English was adapted from the Phonological Awareness Battery (PhAB) (Frederickson, Frith, & Reason, 1997). We used a battery of similar tests developed for Hindi which was validated on a separate group of Hindi–English biliterate children. For the rhyme test in both languages, children were asked to identify the non-rhyming word from a given set of three words. In the spoonerism test, children were instructed to replace the initial phoneme in an English word. Similarly, in the spoonerism test in Hindi, the initial *akshara* was to be replaced with a given *akshara*. Fluency measures were obtained from tests of semantic and alliteration fluency, where children were asked to name objects in a given category and name words beginning with a given sound (e.g. English – /b/, /d/, Hindi – /p/, /t/) respectively within a time limit of 30 s. In the rapid naming test, children were timed while naming two sets of pictures of familiar objects (after a familiarization phase), one in Hindi and the other in English.

2.3. Experimental paradigm

The fMRI paradigms employed reading tasks in Hindi and English in a simple and identical block design. The task comprised