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Age-related differences in effective connectivity of brain regions involved in Japanese kanji processing with homophone judgment task

Chiao-Yi Wu [a], Jia Ying Serene Koh [a], Moon-Ho Ringo Ho [a], Makoto Miyakoshi [b,c,d], Toshiharu Nakai [c], Shen-Hsing Annabel Chen [a,*]

[a] Division of Psychology, School of Humanities and Social Sciences, Nanyang Technological University, Singapore
[b] Swartz Center for Computational Neuroscience, Institute for Neural Computation, University of California San Diego, United States
[c] Neuroimaging and Informatics Lab, National Center for Geriatrics and Gerontology, Ohbu, Aichi, Japan
[d] Japan Society for the Promotion of Sciences, Japan

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ABSTRACT

Reading is a complex process involving neural networks in which connections may be influenced by task demands and other factors. We employed functional magnetic resonance imaging and dynamic causal modeling to examine age-related influences on left-hemispheric kanji reading networks. During a homophone judgment task, activation in the middle frontal gyrus, and dorsal and ventral inferior frontal gyri were identified, representing areas involved in orthographic, phonological, and semantic processing, respectively. The young adults showed a preference for a semantically-mediated pathway from orthographic inputs to the retrieval of phonological representations, whereas the elderly preferred a direct connection from orthographic inputs to phonological lexicons prior to the activation of semantic representations. These sequential pathways are in line with the lexical semantic and non-semantic routes in the dual-route cascaded model. The shift in reading pathways accompanied by slowed reaction time for the elderly might suggest age-related declines in the efficiency of network connectivity.

1. Introduction

Reading, an important aspect in everyday living, enables us to make sense of the surroundings. Fast and accurate recognition of written scripts in reading seems to be an automatic process for normal readers and involves a series of complex sensory and cognitive processes, many of which could be interrupted by several factors such as normal aging. While neuroimaging studies of cognitive aging have revealed age-related differences in brain activity relevant to a variety of cognitive functions such as working memory, episodic memory, semantic memory retrieval, perception and inhibitory control (e.g., Cabeza, 2002; Davis, Dennis, Daselaar, Fleck, & Cabeza, 2008), language-related issues, such as word-finding difficulties, have also been observed in healthy older adults. Behavioral studies have suggested that word-finding failures occur when the connections between lexical and phonological systems weaken due to aging or lack of recent or frequent use. This is often seen in the elderly where more word-finding difficulties are experienced than the young (Burke, MacKay, Worthley, & Wade, 1991; Burke & Shafto, 2004). The mapping between sounds and words/characters may be further complicated in a writing system such as that of Japanese kanji where the pronunciation of a kanji character is dependent on the semantic context in which the character appears. An arbitrary sound could also be allocated to a kanji character as is often seen in names, lyrics or advertisements (Matsuo et al., 2010). In this case, specific cognitive processes or neural strategies might be developed in order to extract phonological sounds from the logographic characters. Yet, little is known about how the neural mechanism of character reading, such as in Japanese kanji, might be influenced by healthy aging.

1.1. Word recognition processes and kanji

One of the most influential cognitive models of reading is the dual-route cascaded model (DRC; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), which posits three possible processing pathways for reading. The first pathway is a lexical semantic route, in which reading requires the association between the visual word forms and their meanings. Successful reading is achieved when the orthographic form of a word activates the corresponding semantic lexicon, which is then

* Corresponding author. Address: Division of Psychology, School of Humanities and Social Sciences, Nanyang Technological University, 14 Nanyang Drive, HSS-04-19, Singapore 637332, Singapore. Fax: +65 6795 5797.
E-mail address: annabelchen@ntu.edu.sg (Shen-Hsing Annabel Chen).

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linked to the phonological output. Second, successful phonological retrieval is possible via a lexical non-semantic route, in which the orthographic forms of characters are directly mapped to the corresponding phonological lexicons without recourse to the semantic system. However, when this lexical mapping becomes difficult or impossible for infrequent or pseudo words, the other route through a grapheme–phoneme correspondance (GPC) system comes into effect. The GPC route requires grapheme-to-phoneme conversion, by which the printed word is decomposed into several graphemes and transformed to phonemic components, and the pronunciation of the word is assembled by all phonemes. The meaning of the word becomes accessible after the pronunciation is available. While grapheme-to-phoneme conversion is applicable in alphabetic languages (such as English and Spanish), it seems impossible for Japanese kanji reading because there is no way to decompose a kanji character into small graphemes that correspond to phonemic components. As Japanese kanji characters are ideograms of which a symbol corresponds globally to meanings and pronunciations, the kanji recognition process may follow the lexical route whereas the GPC route is not applicable. On the other hand, it is worthwhile to note that for Japanese kana, a phonographic system that shares more similarities with alphabetic languages, both lexical semantic and GPC routes in the dual-route model may be adopted (Ischebeck et al., 2004).

The apparent complexity of kanji leads to the questions of how readers extract sounds and/or meanings from the printed word for kanji reading, and what roles the phonological and semantic factors play. In the current study, we aimed to examine the dynamics among orthographic, phonological, and semantic processing in the neural networks of kanji character reading. Five possible pathways were considered. First of all, we began with a parallel model (Model 1) where the orthographic information could activate both semantic and phonological processing with no preference for one or the other. Next, two sequential models were proposed according to the lexical routes in the DRC model (Coltheart et al., 1993, 2001). Here we considered that orthographic processing could either lead to semantic processing followed by phonological processing (Model 2) or lead to phonological processing followed by semantic processing (Model 3). Finally, two more models with the combination of the parallel and sequential pathways were considered. Both models consisted of parallel pathways from orthographic processing to both semantic and phonological processing, but they had an additional pathway either from semantic to phonological processing (Model 4) or from phonological to semantic processing (Model 5).

A number of regions have been identified to be involved in kanji reading. For its visual complexity of character forms, kanji reading was found to activate the inferior occipito-temporal regions, including the bilateral inferior occipital gyri (IOG) and the left fusiform gyrus (FG) (Sakurai et al., 2000; Thuy et al., 2004). It has also been proposed that the left posterior prefrontal cortex plays an important role in kanji reading, specifically with a functional segregation into three segments: the ventral inferior frontal gyrus (IFG), dorsal IFG, and the middle frontal gyrus (MFG), which are associated with selection of semantic, phonological, and morphological information, respectively (Matsuo et al., 2010). In the current study, we employed a kanji homophone judgment task, in which participants were required to judge whether two kanji characters had the same pronunciation. This task was thought to evoke print-to-sound mapping to retrieve the pronunciations, and thus would be a suitable task to examine the modeling pathways in the kanji recognition process. Based on the findings in the prior neuroimaging studies, we selected the following regions to examine effective connectivity of the proposed models: the left IOG (BAs 17/18), the left FG (BA 37), the left MFG (BA 9), and the left IFG. The left IFG was divided into ventral IFG (BA 47) and dorsal IFG (BA 44) as previous studies have suggested that the dorsal IFG is involved in phonological processing and the ventral IFG is associated with semantic processing during word recognition (Poldrack et al., 1999; Wu, Ho, & Chen, 2012). Along with the functional segregation in the left posterior prefrontal region proposed by Matsuo et al. (2010), the MFG, dorsal IFG, and ventral IFG were proposed to represent orthographic, phonological, and semantic processing regions in the kanji reading network.

1.2. Aging and language

Much neuroimaging research has found that aging comes along with declines in a variety of cognitive functions, such as memory, executive function, and attention, and these declines are associated with changes in brain activity. However, less is known about age-related changes in the neural mechanism underlying language processing. The lack of aging literature in language could possibly be due to the understanding that verbal ability, considered as a domain of crystallized intelligence, has been found to be less affected by aging. Crystallized intelligence is the intellect gained from knowledge or experience, and past studies have shown that crystallized intelligence was higher for older adults (Horn & Cattell, 1967). For verbal abilities, studies have also shown that vocabulary increased with age (Verhaeghen, 2003), specifically showing increments to the middle age, reaching a plateau to the early-old age, and only showing modest decrements in the old–old individuals (i.e., 75 years old and above) (Giambra, Arenberg, Zonderman, Kawas, & Costa, 1995).

Despite the notion that language may be relatively preserved as we age, older adults tend to have more language-related complaints than young adults, such as word-finding difficulties (Burke et al., 1991; James & Burke, 2000) and difficulties in picture/object naming (Van Gorp, Satz, Kiersch, & Henry, 1986; Zec, Burkett, Markwell, & Larsen, 2007). Recently more neuroimaging studies have started to investigate age-related functional changes in the brain activity during language processing, and changes in regional activity have been observed in the frontal regions (e.g., Meinzer et al., 2009, 2012; Shafto, Stamatakis, Tam, & Tyler, 2009). Age-related declines in white matter integrity, especially in the frontal brain areas, have also been reported (Pfefferbaum, Adalsteinsson, & Sullivan, 2005; Salat et al., 2005). Moreover, the alterations in structural and functional connectivity within the language networks in healthy aging might be associated with deterioration of cognitive performance (Antonenko et al., 2013). Therefore, the combined influence of aging on regional brain activity as well as structural and functional network connectivity brought up a question of whether older adults might adopt a differential pathway for reading as compared to young adults. In particular, we hypothesized that the connections between language-related regions might be modulated by task conditions differentially with respect to age. To the best of our knowledge, no studies have investigated age-related effects on effective connectivity within language networks. Hence, it is important for the current study to fill this gap.

1.3. Study aims

Effective connectivity analysis with fMRI allows us to investigate how activated brain regions are connected under a task circumstance as well as how the regions and connections within this network might be modulated by external stimuli. Hence, to elucidate the neural pathways underlying kanji character processing, dynamic causal modeling (DCM) was selected in the current study to examine alternative models of reading. Through functional neuroimaging, we evaluated the processing pathways within the neural network of kanji reading in young and elderly Japanese speakers. Findings from the current study will provide further