Brain and writing: Cognitive aspects of writing systems and numerical processing

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Writing systems in the world

The number of currently used writing systems in the world is staggering, as can be seen from the amount of scripts in the Unicode standard. The Unicode includes over 64 000 characters that are needed to write texts in the modern world. Some scripts, such as the Latin alphabet, include only 27 letters in its simplest form (plus upper case versions), though they are sufficient for one language only. On the other hand, Chinese script contains tens of thousands of characters in different varieties. Moreover, many extensive historical systems have disappeared from use, such as the Egyptian hieroglyphs, Sumerian cuneiform, or Maya characters. (Gaur, 1984) (Haarmann, 1990)

Contemporary writing systems can be classified to three major kinds of systems: Greek-derived alphabets including the Arabic consonant system, Chinese ideograms and other East Asian systems based on them, and syllabic writings in South Asia. Historically, the Arabic and alphabetical writings share common origins in hieroglyphs.

Scripts

The Western Latin alphabet is one of the simplest writing systems in terms of linear organization and number of characters. It is closely related to other Greek-derived alphabets such as the Cyrillic (Russian) script. However, the way it is applied in a particular language varies considerably: the relation between spoken and written language is historically created and changes over time, which can be observed in comparing English, Italian and French or other European languages. The orthographic rules in each language are different. Moreover, special symbols appear in the writing of most languages in order to indicate pronunciation more closely. Nevertheless, the written language seldom reflects well the current status of pronunciation, and only few languages have a truly transparent orthography.

This is the case in for example for Finnish, the language of Finland, which is written almost exactly the way it is spoken. Czech, Italian, and Korean are very near the phonetic ideal, as well, and even Spanish, which is spoken in many countries comes quite close to it.

The Arabic consonant system is historically related to alphabets, but, significantly, it is written from right to left. In addition, other varieties of the alphabetic or consonant systems include Hebrew, Georgian, Armenian and Urdu.

Chinese is the oldest widely used writing system. There are approximately 50,000 characters, of which a couple of thousands in everyday use. The writing system in many ways fits well to the language. Chinese words are typically short consisting only of one or two syllables. Words are not inflected, either, which means that there are no endings or different word forms. The language has a great amount of homonyms, as there are only about 600 different syllables. Spoken Chinese has many tones which change the meaning of the word. The tonal system includes a high pitch and a high-rising pitch, a low-falling-rising pitch, and a high-falling pitch, depending on the dialect, as well. A Chinese word written with the Latin letters 'shu' has at least 25 different meanings, including a center, a private school, a potato, a rat and talent. When written with Chinese characters, every meaning has its own particular character.

Chinese characters are drawn to fill an equally large space. They are drawn in certain order: a horizontal line before a vertical line, the left part before the right part, and the upper part before the lower part. The characters may look very confusing for an untrained eye, but once a person learns about the basic components of the characters they become easier. For example the character 安(an) has a top part with 3 strokes and a lower part of 3 strokes. The perception of an individual character is visually more demanding than for alphabetic letters, as one character may consist of 13 strokes. Chinese is written in varied directions, including from left to right.

The various syllabic writings in South and South-East Asia tend to be visually demanding and complex, as well. One syllabic character is a combination of elements that define its consonant and vowel content. They are mostly based on an ancient Gupta script, and among them the Indian Devanagari script is most widely used. However, the variety of languages that used this kind of writing, includes also Thai and Lao that are closer to Chinese is some features.

Korea is a neighbor of China, and got its first writing system from the Chinese. By the 15th century, the Koreans were familiar with the Indian Devanagari script, as well. King Sejong was a learned person who was not satisfied with the use of Chinese characters to write Korean, which is a different kind of language. He set up a committee of eight learned persons to draft a writing perfectly suitable to the Korean language. The committee worked for three years and it did its job well: it developed the most scientific writing ever used called Hangul.

It is based on 5 consonants and 3 basic vowels which are combined to phonetic units, syllables. The shape of consonants is derived from the shape of mouth and throat when they are said. The vowels, on the other hand, are derived from cosmology: 'O' is the symbol for the sky, 'ü' is for the earth and 'i' for the human being. 'A' is a combination of human and sky which gives a tree, and 'u' is sky under the earth, which means 'fire'.

Hangul characters look like this: ㅃ ㅇ ㅉ ㅙ

The total number of combination characters or syllables in the Korean language is 2,300 (this is much more than the Chinese 600). But instead of learning the combinations by heart, Koreans need to understand the combination principles.

The Japanese writing combines three scripts: the Chinese-origin kanji characters, and two syllabic kana character sets.

Studies in reading and writing

It is approximately known *where* main cognitive functions are located in the brain. The language areas have already been known for decades, but still there is no certainty *how* cognitive processes actually function (Kitayama & Park, 2010). Certain brain areas are essential for certain activities, but in addition, a network of other areas might be involved as well, which is the case for language processing. Moreover, understanding and producing language consists of many separate activities: understanding speech, talking, reading, and writing. Keeping theses separate in research setting might be challenging.

Most of the research concerning language and number processing has been done using Indo-European language speakers (English, German, Italian, French) who read alphabetic characters and use Arabic numerals. A comprehensive research program to study language functions in the brain would ideally include many types of languages and many different writing systems. Ideally, the cases would represent “pure” types of writings such transparent orthographies on the other hand, and ideograms on the other hand.

The research into the varied effects of other than alphabetic writing systems on cognition has commenced recently, especially in Japan and China, but most of the world’s writings remain largely unexplored from the neuroscientific perspective. (Kitayama & Park, 2010)
Writing Chinese characters requires good hand movement control and visual memory, therefore it has been found that the Chinese employ visuo-motor brain areas for reading and writing to a much larger extent than alphabet users. Intensive research concerning processing of Chinese and Japanese languages has revealed significant differences in brain networks that are involved in reading logographic or alphabetic texts. (Bolger;Perfetti;& Schneider, 2005) (Xu;Wang;Chen;Fox;& Tan, 2015) An extensive overview of what was known by the time of writing in 2009 on processing of numbers and text in the brain cross-culturally is offered by Chen *et al* (Chen;Xue;Mei;Chen;& Dong, 2009). They give more examples of cognitive linguistics than can be presented here, plus summarize the brain locations involved in the processing as far as they can be indicated.

Dyslexia has already been shown to be caused by dysfunction in different brain areas in Chinese readers compared to English readers, and there is increasing evidence of differences in processing numbers, arithmetic, etc. in people who use predominantly ideographic characters (Ting Siok;Niu;Jin;Perfetti;& Tan, 2008)

In one of the recent studies on Chinese reading, Yang *et al* (2011) identified from fMRI data a typical ”reading network” in Chinese readers that showed evidence for stimulus selectivity in a much broader network. Throughout the reading network, activity was largely modulated by task difficulty, but some regions showed selectivity for particular forms of sublexical information. The results were consistent with models in which sublexical processing is a natural part of reading in Chinese. (Yang;Wang;Shu;& Zevin, 2011) .

An other study compared eye movements of native English speakers, native Chinese speakers, and bilingual Chinese/English speakers who were either born in China (and moved to the US at an early age) or in the US. The eye movements were recorded during six tasks: (1) reading, (2) face processing, (3) scene perception, (4) visual search, (5) counting Chinese characters in a passage of text, and (6) visual search for Chinese characters. Across the different groups, there was a strong tendency for consistency in eye movement behavior; if fixation durations of a given viewer were long on one task, they tended to be long on other tasks (and the same tended to be true for saccade size). Some tasks, notably reading, did not conform to this pattern. Furthermore, experience with a given writing system had a large impact on fixation durations and saccade lengths. Chinese participants’ fixations were more numerous and of shorter duration than those of their American counterparts while viewing faces and scenes, and counting Chinese characters in text. (Rayner;Li;Williams;Cave;& Well, 2007)

Recently, a considerable research effort has examined the relationship of orthographic and phonological processing in children at different ages, which seems to indicate that they are intertwined even when it is not required by the task. (Cone;Burman;Bitan;Bolger;& Booth, 2008).

Rudell and Hu measured reaction times of Native English speakers and ESL speakers of Chinese origin, to compare the effect of long-time reading experience on recognition potential (Rudell & Hu, 2010). Their study indicates that long-time reading experience made recognition of English words faster, even when the words were short and simple.

Very few studies on other writing systems have been conducted. Recently, Indian researchers have scanned the brains of Devanagari (a syllabic script) readers. (Singh & Rao, 2014). They conclude that “distinct from alphabetic scripts, which are linear in their spatial organization, and recruit a primarily left-lateralized network for word reading, our results revealed a bilateral reading network for Devanagari. We attribute the additional activations in Devanagari to increased visual processing demands arising from the complex visuospatial arrangement of symbols in this ancient script.”

Studies in numbers and mathematics

Numbers and mathematical skills have been studied by anthropologists and historians, who have found the fascinating variety of number systems in the world. Despite the diversity of indigenous mathematical systems, counting and arithmetic ability seems to be the same everywhere, only the tools differ. Even other mammals have a rudimentary numerosity skill, and a numerosity awareness has been found in infants, as well. Natural numbers develop in the same brain area where magnitude representation is located. (Cohen Kadosh;Lammertyn;& Izard, 2008) Many animals are sensitive to numerical regularities in their environments, can represent these regularities internally, and can perform elementary and approximate computations with numerical quantities.

Thomas Crump (1990, 19) who has written an anthropology of numbers believes that the human brain has a certain capability for mathematic operations and the diversity of skills and intelligence is on individual, not cultural level as such. He believes that symbolic counting is a universal skill that develops gradually with age and is relatively unaffected by variations in the counting system employed, culture, cognitive development and schooling. He sees that the reason is in the structure of mathematics that is in some sense isomorphic with the structure of reality. The cross-cultural differences in scientific worldviews are large, but the existence of many advanced scientific systems (Greek, Arabic, Indian, Chinese, Mesoamerican, Egyptian, modern Western) indicates that humans have an innate aspiration for scientific understanding, and a capacity to develop sophisticated mental models.

A recent issue of Journal of Cross-cultural psychology (May 2011) was devoted to numerosity skills, and the mental number line concept in particular. According to the new research presented in that issue, several cultural factors influence how people, and especially young people and children, perceive the number line, but there is no clear-cut dependence between the language, writing direction, handness, or the numeral system and the studied numerosity skills: finger counting, number line, and estimation of value. The effects of each factor seem to be complex and vague, allowing a large amount of individual variation.

The dominant theory of an innate, universal number line in the brain has been reviewed in several studies, and the view that humans share an intuition that numbers map onto space has been challenged. Particularly an oriented left-to-right mental number line (MNL) has been found to be culturally produced, and appearing mainly in Western culture. The mechanisms of number-to-space mappings appear to be acquired through education, and are biologically realized through the systematic consolidation of specific brain phenotypes. (Göbel;Shaki;& Fischer, 2011) (Núñez, 2011)

The universal use of Arabic numbers in mathematics raises a question whether these digits are processed the same way in people speaking various languages, such as Chinese and English. Using functional MRI, a research group by Tang et al demonstrated a differential cortical representation of numbers between native Chinese and English speakers. (Note that Chinese have their native numbers in addition to Arabic numerals.) Contrasting to native English speakers, who largely employ a language process that relies on the left perisylvian cortices for mental calculation such as a simple addition task, native Chinese speakers, instead, engage a visuo-premotor association network for the same task. Whereas in both groups the inferior parietal cortex was activated by a task for numerical quantity comparison, functional MRI connectivity analyses revealed a functional distinction between Chinese and English groups among the brain networks involved in the task. The results further indicate that the different biological encoding of numbers may be shaped by visual reading experience during language acquisition and other cultural factors such as mathematics learning strategies and education systems, which cannot be explained completely by the differences in languages per se. (Tang *et al.* 2006) Already a study by Campbell *et al* (Campbell;Kanz;& Xue, 1999) suggested that different notation language combinations, whether Arabic or kanji numerals, were mediated by independent associative paths that varied in strength and efficiency as a function of prior experience.

In another study, Japanese students were taught to read Roman numerals. (Masataka *et al*. 2007) The Japanese use Arabic and kanji (Chinese) numerals, and write two native syllabaries (hiragana and katakana) in addition to using Chinese kanji characters and Latin alphabet. The students who were subjects of this study were not familiar with Roman numerals. The study examined the neuronal correlates of reading Roman numerals and the changes that occur with extensive practice. Subjects were scanned by functional Magnetic Resonance Imaging (fMRI) three times the first day of the experiment and once following two to three months of practice. This allowed comparison of brain activations with varying levels of practice. The results revealed that upon learning that the alphabetical symbols had numeric meaning, subjects immediately activated a network of brain areas, many of which have been previously implicated in numerical processing. Subsequent practice led to a change in the pattern of neuronal activity in a single region of the mid-dorsolateral prefrontal cortex in the left hemisphere. However, Roman numerals were still processed as calculations and not automatically recognized as number patterns. The result is very interesting because it implies that internalizing numbers takes a long time, as it was not achieved in three months' time in young adults.

Coderre *et al*. (2009) compared reactions to kana, kanji and Arabic numerals in Japanese subjects, finding no difference in behavioral reaction time between kanji and Arabic numbers. Liu *et al* (Liu, 2011) emphasize that numerical information can be conveyed by either symbolic or non-symbolic representation in Chinese characters, and that such multi-representation of magnitude has a speed advantage in processing, as well as lower error rates. Cao, Li and Li (Cao;Li;& Li, 2010) also detected differences in speed and distribution activation in the brain in the processing of three different numerical representations (kanji, complex Chinese numbers, and Arabic numbers) by Chinese subjects.

The processing of quantifiers and numbers seems to take place in the same brain domain (Cappelletti *et al*. 2006) where also numeric magnitude and number symbols are processed (Piazza *et al* 2007).

A letter-specific area (alphabetic letters) has been located in the left extrastriate cortex (Flowers *et al.* 2004). However, the processing of encyclopedic numbers (mixed with letter codes) is separate from numbers (Cappelletti;Jansari;Kopelman;& Butterworth, 2008). Already the groundbreaking study by Polk and Farah indicated that separate brain regions are specialized in numbers and letters, and the processing does not overlap, or if it overlaps, it requires considerably more effort. It was shown that processing of Canadian or UK postal codes, such as KY169UH, that mix numbers and letters is difficult and requires more concentration than exclusively numerical or alphabetical codes (Polk & Farah 1998). Nevertheless, postal workers develop a brain mechanism to treat them together after practice.

A separate case from numerical processing seems to be higher order mathematics and formal conclusion. A particularly important class of formal languages are those underlying the mathematical syntax. Friedrich and Friederici have found brain-imaging evidence that the syntactic processing of abstract mathematical formulae, written in a first order language, is, indeed efficient and effective as a rule-based generation and decision process. “However, it is remarkable, that the neural network involved, consisting of intraparietal and prefrontal regions, only involves Broca's area in a surprisingly selective way. This seems to imply that despite structural analogies of common and current formal languages, at the neural level, mathematics and natural language are processed differently” (Friedrich & Friederici 2009).

For the development of abstract and scientific thought, mastery of the language is required (Haag;Heppt;Stanat;Kuhl;& Pant, 2013). Even mathematical skills are influenced by the language of instruction, as was shown by Saalbach *et al* (2013). According to their study, when the language of instruction and language of application differed, performance in arithmetic tests deteriorated. There was a significant cognitive cost involved even in this case where the subjects of the study came from a privileged Swiss German and French school system.

Cross-cultural studies

Cross-cultural psychology is concerned in individual behavior that could be influenced by the culture. Study of cognitive differences is a small part of the field. It has traditionally been limited to a few prominent questions, such as, the differences in color perception, understanding perspective in pictures, and visual perception more generally; the influence of language to thinking, and eventual differences in intelligence (Berry;Poortinga;Segall;& Dasden, 2002).

A significant proportion of cross-cultural psychological studies look at differences in color terms, asking 1) are the basic colors everywhere the same, 2) does the naming of the color affect thinking/ perception? Necessarily, the findings on cognition remain vague: culture has some influence on certain behavior, but usually the individual variety is larger. Guy Deutscher (Deutscher, 2010) has written an entertaining popular book on this subject where he tells the history and fluctuations in scientific attitudes towards the interplay of culture and biology by cases of color perception and the influence of language to thinking.

Other modalities have not attracted much research, but it is known from genetic studies that humans in different populations have different abilities in tasting and smelling, and propensity for chemical addictions differs. Additionally, decision-making and perception seem to be influenced by culture.

Behavioral differences in the visual processing of objects and backgrounds as a function of cultural group have been discovered: North Americans seemed to focus on the object more than East Asians who perceived the environment and context (Nisbett & Masuda 2006). Neuroimaging evidence also points to cultural differences in neural activation patterns that develop during adulthood. Compared with old East Asian adults (test subjects about 67 years), Westerners of the same age have more object focused visual processing, and they activate neural structures that reflect this bias for objects. In a recent adaptation study, East Asian older adults showed an absence of an object-processing area but normal adaptation for background areas. (Goh *et al*. 2007) However, the results do not go unchallenged, as no difference was observed in another study (Rayner *et al* 2007).

Several studies have shown that working memory performance is predictive for mathematics and linguistics abilities (Libertus;Brannon;& Pelphrey, 2009). Additionally, Boles (Boles, 2011) shows that socio-economic background influences brain lateralization, such that a nurturing environment advances the development.

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