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Distinct representations of symbolic ordinality and quantity: Evidence from neuropsychological investigations in a Chinese patient with Gerstmann's syndrome

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ABSTRACT

A number of recent studies have shown conflicting evidence as to common or distinct representations between symbolic ordinality and quantity. We investigated this issue through a series of neuropsychological tests in a unique Chinese patient with the left angular gyrus and left supramarginal gyrus lesions. Behavioral experiments revealed that (1) the patient showed Gerstmann syndrome, with minimal anomia and alexia and (2) the patient showed the dissociation among number semantic representations with relatively preserved symbolic quantity knowledge and impaired processing of symbolic order meaning. Together with existing evidence in the literature, results of the current study suggest that there might be two separate cognitive representations of symbolic ordinality and quantity in logographic language according to this dissociation. Most importantly, another merit of this study is that the left angular gyrus and left supramarginal gyrus might be necessary to symbolic ordinality representation.

1. Introduction

When thinking about numbers, there would be many kinds of meanings according to the context in which they are used (Jacob & Nieder, 2008). Firstly, it can denote numerical quantity, or cardinality, which has been extensively investigated. It is argued that the ability of quantity processing is part of a "cognitive core knowledge" associated with evolutionarily ancient and specialized cerebral subsystems (Cantlon, Platt, & Brannon, 2009; Dehaene, 1992; Feigenson, Dehaene, & Spelke, 2004; Spelke, 2000). Secondly, it can signify the position of an item in an ordered sequence, called ordinality, which is considered to be a multidimensional construct involved in numerical processing (Jacob & Nieder, 2008; Nieder, 2005), reading (Davis, 2010), planning, and learning (Gobel, Parrish, & Reber, 2011). In addition, it is argued that the numerical dimension of ordinality is a basic perceptual cognitive construct (Rubinsten, Dana, Lavro, & Berger, 2013). In contrast, the nature of ordinality has received relatively less research attention, despite the fact that both quantity and ordinality are embodied in numerical information. Finally, number can also bear other different meanings, such as counting and numerical labels. However, more attention has been paid to the relationship of numerical quantity and ordinality processing in recent years. There are two competing theories regarding the neural basis of quantity and ordinality processing.

The first theory proposes that mental processing of cardinal and ordinal numbers is based on neural networks housed within the same cortical structures. The most important line of evidence supporting this theory comes from a common representation for ordinality and quantity has been suggested by functional magnetic resonance imaging (fMRI) studies reporting similar brain regions activated by processing ordinality and quantity information (Fias, Lammertyn, Caessens, & Orban, 2007; Fulbright, Manson, Skudlarski, Lacadie, & Gore, 2003; Ischebeck et al., 2008). It is argued that the anterior part of the horizontal segment of the intraparietal sulcus (hIPS) codes numerical quantity (Dehaene, Piazza, Pinel, & Cohen, 2003), however, the specific role of hIPS in number processing might be to represent ordinality rather than just quantity (Nieder, 2005). Other studies demonstrated that systematically stronger hIPS activation during the processing of numbers than for non-numerical ordinal dimensions such as letters (Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003), animal ferocity (Thioux, Pesenti, Costes, De Volder, & Seron, 2005), or body part position (Le Clec et al., 2000), indicating that hIPS activation does not relate to the processing of ordinal information in general, but

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of quantitative information specifically (Piazza & Dehaene, 2004). However, the authors regarded these studies could not be considered conclusive due to limitations of different experiment tasks (Fias et al., 2007). Firstly, body position or animal ferocity may not be stored as ordinal dimensions in long-term memory, but may be created only for temporary task demands. Secondly, letters were investigated using an order-irrelevant letter identification task, and explicit processing of order may be required to activate hIPS (Fias et al., 2007). Because alphabetic order is stored in long-term memory and because the comparison task requires explicit processing of order, the authors used letter comparison to investigate the hIPS involvement in the processing of quantity and ordinality (Fias et al., 2007). It is demonstrated that the bilateral intraparietal sulci (IPS) were activated by both a numerical quantity task and an order task (Fias et al., 2007), suggesting that mental processing of cardinal and ordinal numbers is based on neural networks housed within the same cortical structures. It was also revealed activation of the IPS for both ordinality and quantity processing, although they showed different numerical distance effects which may suggest independent cognitive mechanisms being used (Franklin & Jonides, 2009). However, it is noted that Van Opstal et al. found that the absence of IPS activation in the representation of a learned ordinal sequence, which indicate that there is no need for an IPS area specifically dedicated to the representation of all ordinal sequences (Van Opstal, Fias, Peigneux, & Verguts, 2009). Hence, the authors proposed that the locus of the representation might be determined by the nature of the stimuli rather than its ordinal nature per se (Van Opstal et al., 2009). Another important line of evidence supporting this theory comes from neuropsychological studies of patients with brain lesions, which could offer an insight into the organization and the neural basis of cognitive processes. Cipolotti et al. investigated a patient with Gerstmann's Syndrome through a series of number processing and number knowledge tests. The patient showed both a severe and selective deficit in processing numbers and poor performance on reciting non-numerical sequences such as letters, days of the week and months of the year (Cipolotti, Butterworth, & Denes, 1991). In terms of neural processing, quantity and ordinality might just be two sides of the same coin.

The second theory states that there might be two separate cognitive representations of quantity and ordinality processing. The strongest evidence comes from neuropsychological studies with brain-damaged patients, which showed that ordinality and quantity information dissociated at both the behavioral and biological levels (Delazer & Butterworth, 1997; Turconi & Seron, 2002). In addition, Rubinsten and Sury (2011) investigated the relation between ordinal and numerical information processing through two novel experiments of ordinal processing in typically developing adults and adults with developmental dyscalculia (DD), which indicated that quantity and ordinality meanings might refer to distinct representations (Rubinsten & Sury, 2011). These findings bear a striking resemblance to some ERP studies. An ERP study showed separate mechanisms both in terms of timing and topography for ordinality and quantity information (Rubinsten et al., 2013). Another ERP research argued quantity and ordinality were associated with different spatio-temporal courses in parietal and prefrontal cortices, though both quantity and ordinality show similar behavioral effects (Turconi, Jemel, Rossion, & Seron, 2004). Furthermore, Cheng et al. found there are at least partially different neuronal populations involved in ordinality and quantity processing, and that the left parietal cortex is critical for both processes, through continuous theta-burst stimulation (TBS) study (Cheng, Tang, Walsh, Butterworth, & Cappelletti, 2013). Although several recent fMRI studies suggest that the anterior region of the IPS may be involved in the abstract representation of ordinality processing that is not number-specific (Fias et al., 2007; Fulbright et al., 2003; Ischebeck et al., 2008), Zorzi, Di Bono, and Fias (2011) found a clear dissociation between processing numerical vs. alphabetical orders in bilateral horizontal IPS through using support vector machines to reanalyze the data of Fias et al. (Fias et al., 2007). The results show that multivariate analyses are mandatory to tackle subtle but important distinctions (for cognitive theory) such as cardinal vs. ordinal information or numerical vs. non-numerical ordered sequences (Zorzi et al., 2011). In addition, Tang et al. found there are separate but partially overlapping neural circuits for the processing of ordinal and cardinal numbers, irrespective of the presence of a number form (Tang, Ward, & Butterworth, 2008). Hence, quantity and ordinality processing may be based on neural networks housed within the overlapping cortical structures.

In summary, the studies have yielded conflicting results in alphabetic languages: some evidence suggest that quantity and ordinality processing share the same neural system, while other studies indicate two separate cognitive representations of quantity and ordinality information. In addition, it is noted that Arabic numbers are used universally in people speaking various languages, such as Chinese and English, however, these digits may be processed in the different way (Tang et al., 2006). Written Chinese, often called a "logographic" writing system, is composed of strokes and subcharacters that are packed into a square configuration, possessing a high, nonlinear visual complexity. Reading and learning to read Chinese characters may place very high demands on visuospatial processing and rely on memorizing the obligatory relationships between the lexical entries and their pronunciations/ and meanings (Tan et al., 2003; Tzeng, Hung, Cotton, & Wang, 1979; Zhou & Marslen-Wilson, 1999), which have led to the reasonable assumption that processing Chinese characters involves the right hemisphere (RH) more than does the processing of alphabetic scripts.

There are relatively fewer studies of number processing in Chinese reported studies compared with the large number of researches in alphabetic languages. Tang et al. use fMRI to show the inferior parietal cortex was activated by a task for numerical quantity comparison in both native Chinese and English speakers. However, a functional distinction between Chinese and English groups was found through fMRI connectivity analyses, which indicates the different biological encoding of numbers in Chinese and English (Tang et al., 2006). In addition, in a study of Chinese readers in Taiwan, the results has also shown that cultural factors such as the layout of printed words and daily experience with numbers may influence the spatial–numerical association of response codes (SNARC) effect (Hung, Hung, Tzeng, & Wu, 2008). Furthermore, in a recent study, Zhao H et al. found differences in neural mechanisms underlying the learning and representation of magnitude and spatial order through using an artificial symbol learning paradigm and the ERP technique (Zhao et al., 2012). It is noted that the study revealed difference in hemispheric asymmetry of magnitude and order learning. The training effect was right lateralized for magnitude learning, but bilateral for order learning. The authors argued that the results of generally rightward bias in laterality may involve the way Chinese language is processed (Zhao et al., 2012), which is consistent with previous studies (Tan et al., 2000; Tang et al., 2006). However, it is hard to say whether ordinality and quantity information are processed in the same way or not in people speaking logographic languages, because there is litter evidence from fMRI or lesion studies.

Although functional neuroimaging studies of normal subjects could identify the structural areas where metabolism changes with changes in function, it could be considered the inherent limitation: significant activation in response to one task relative to another does not indicate whether the activation is necessary for correct performance (Price et al., 2003). Determining whether an area is necessary for one task requires a consideration of whether a lesion