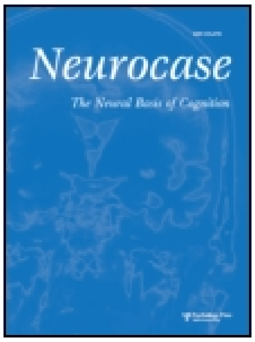

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Double dissociations of word and number processing in auditory and written modalities: A case study

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We report an individual with a massive left-hemisphere lesion, who showed reverse patterns of dissociations between word and number processing in two modalities (auditory comprehension and written production). His performance in auditory comprehension was perfect for words, but severely impaired for numbers. In written production, he performed significantly better at writing numbers (both Arabic numbers and word numbers) than writing words. His visual comprehension fell into normal range for words and numbers while his oral production was at floor for both. This case profile adds further evidence to the functional/neural segregation of word and number processing systems.

Keywords: Word processing; Number processing; Double dissociation; Case study; Chinese.

It is an open issue whether words and numbers are processed in common cognitive and neural systems. A generic framework for processing both types of symbols across various modalities has been proposed, incorporating the auditory input, visual input, oral production, and written production modules contacting a central semantic representation (e.g., Caño, Rapp, Costa, & Juncadella, 2008, see Figure 1). It has been reported, however, that the dissociations between words and numbers in brain-damaged populations could originate from the semantic system (e.g., Butterworth, Cappelletti, & Kopelman, 2001; Cipolotti, Butterworth, & Denes, 1991; Thioux, Pillon, Samson, de Partz, Noël, & Seron, 1998), auditory input modality (Caño et al., 2008) and phonological output modality (e.g., Marangolo, Piras, & Fias, 2005). Word–number dissociations could also be seen in reading and at a more peripheral level, such as at the phonemic pattern encoding for speaking or the graphic motor program retrieval process for writing (e.g., Anderson, Damasio, & Damasio, 1990; Cohen, Verstichel, & Dehaene, 1997; Delazer, Lochy, Jenner, Domahs, & Benke, 2002). Furthermore, it has been observed that word–number dissociations could be between different categories (i.e., words vs. numbers, e.g., Butterworth et al., 2001; Caño et al., 2008; Marangolo et al., 2005; Messina, Denes & Basso, 2009) or between different scripts (Arabic script vs. verbal script, e.g., Anderson et al., 1990; Cohen Kadosh, Henik, & Rubinsten, 2008; Delazer et al., 2002).

A further interesting issue concerns whether the relationship between word and number processing is universal across languages. All previously reported individuals with selective deficits for processing words or numbers have been speakers of Indo-European languages (e.g., English). Given the general similar functions of words and numbers across languages, dissociations between number

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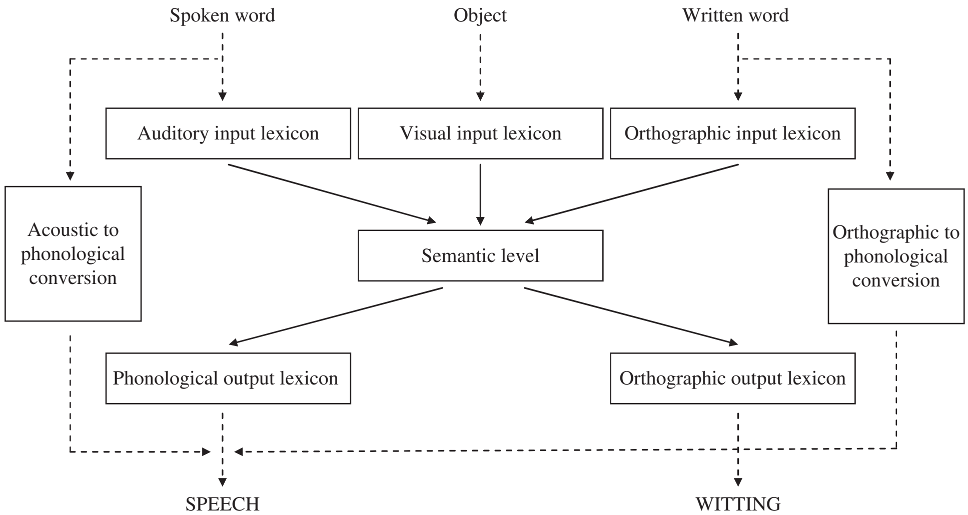

Figure 1. Architecture of processing of numbers and other class of words. (Adapted from Caño et al., 2008; more detailed processes are shown by dashed lines for simplicity.).

and word processing are also expected in languages of other families, such as Chinese. Similar to Indo-European systems, two types of scripts for numbers are used by Chinese speakers: Arabic numbers (e.g., 4) and word numbers (e.g., 四), which are pronounced the same (/*si4*/). Note that there are an additional set of word numbers (e.g., 肆) that are used only in very few specific settings (e.g., formal way of writing a check) and will not be discussed further. The word numbers share common phonological and orthographic characteristics with regular Chinese words/characters. For instance, the number '四' (four) are homophones of characters 寺 (temple), 似 (similar), 伺 (wait), 祀 (offer sacrifice), etc.

Here we report a Chinese individual (ZY) showing reverse patterns of dissociations between word and number processing in two lexical modalities: auditory input and written output. The significance of this case is three-fold. First, to our knowledge, this is the first reported case showing the word–number dissociation that originates from the lexical access stage in written output, as previously reported patients exhibiting the word–number dissociation in written-output were attributed to post-lexical stages (e.g., Anderson et al., 1990; Delazer, et al., 2002). Second, the presence of the double dissociations within the same case further strengthens the previous findings of word–number dissociation in a single modality (e.g., auditory input, Caño et al., 2008; Marangolo et al., 2005). Finally, we confirm that word–number dissociation is a principle beyond the Indo-European system and further demonstrate that word–number dissociation could be categorical (i.e., words vs. numbers) in Chinese writing. Our case provides new support for the claim that words and numbers constrain independently the organization of lexical processing modalities in the brain.

CASE REPORT

ZY is a 39-year-old, right-handed, Chinese-speaking male with a junior high school education. He has been in the military service, worked as a driver and is currently a cleaner. He suffered a car accident in 1996, causing a massive lesion involving the left frontal, temporal and parietal lobes (see Figure 2). Subsequently he had severe speech deficits and could barely produce any speech sound. His limited communication means were gesturing and some reading/writing. He could do daily chores such as shopping, watching TV, and playing video-games. ZY was tested on the following word and number tasks during 2007–2009 and he remained stable during this period. The performances of five healthy control participants with comparable age and education to ZY (4 males; mean age: 39.6 years; education: junior high school) were also collected. The statistical methods developed by Crawford and Garthwaite (2005, 2007) were employed for detecting deficits and between-task dissociations.

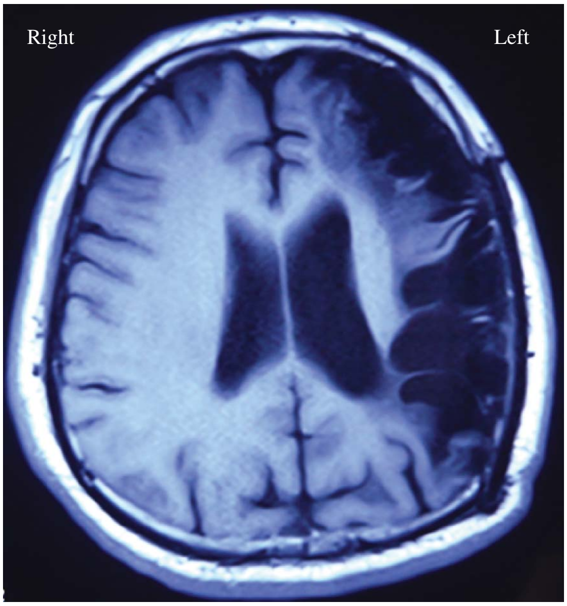

Figure 2. MRI imaging of ZY.

PRELIMINARY ASSESSMENT

To preliminarily assess ZY's processing abilities of words and numbers, we first carried out a set of conventional neuropsychological tasks (e.g., Butterworth et al., 2001; Caño et al., 2008; Marangolo et al., 2005) across four modalities (see Figure 1). For the number items, we used Arabic numbers and did not include word numbers. This was because the goal here was primarily to reveal any word–number dissociation, regardless of it being categorical (i.e., words vs. numbers) or due to script difference (i.e., verbal vs. Arabic). The origin of any potential word–number dissociation was further investigated by comparing words to both word numbers and Arabic numbers in the Experimental Study section.

In visual comprehension, ZY was perfect or near-perfect for both words and numbers. Word tasks included visual word–picture matching (50/50, correct rate; matching one visual word onto two pictures), visual word classification (36/36, classifying words into semantic categories) and visual lexical decision (18/20). Number tasks included visual number comparison (40/40, judging which of the two visually presented numbers was greater), visual addition and subtraction (54/54, addition and subtraction of numbers with 1, 2, and 3 digits), visual number parity judgment (20/20), number bisection (30/30, writing down the midline number for a number pair, e.g., 2, 8 –> 5), chip-selection (29/30, picking the right number of chips for a target number), and thermometer marking (30/30, marking the relative positions of a target number on a hypothetical thermometer with degree of 1–100).

For auditory comprehension, ZY's performance on words was at ceiling and on numbers was severely impaired. He was near perfect in the word tasks: auditory lexical decision (19/20) and auditory word–picture matching (50/50). By contrast, he had great difficulty with number tasks which had the same stimuli as the visual number tasks: he performed at chance in auditory number plausibility decision (10/20, judging whether a spoken sequence was a legitimate number) and auditory number comparison (20/40), and very poorly at auditory addition and subtraction (0/54) and chip-selection (9/30). His performances in the auditory number comprehension tasks were all significantly worse than those of controls ($ps < .0001$).

In oral production, his performance was poor for oral word reading (0/20), oral picture naming (6/82), and oral number reading (8/38), which were all significantly worse than the control group ($ps < .0001$).

In written production, he had severe difficulty with words (written picture naming, 7/82), and was perfect with numbers: spontaneous writing (58/58, writing the following or the previous 10 numbers to a target number). He performed well in delayed copying of words and numbers (all 16/16).

EXPERIMENTAL STUDY

Given that words and numbers in the tasks reported above tend to differ systematically (e.g., visual surface frequency and syllable frequency, number of strokes/characters and syllables), we conducted a set of experiments to consolidate the double dissociation patterns (in auditory input and written production) using comparable tasks for words and numbers with relevant factors controlled for. Auditory comprehension and written production abilities were of particular interest here, with the visual comprehension ability also investigated (see Table 1). The oral production modality was not included because of his extreme difficulty. The values of frequency for the items were extracted from the Chinese corpus developed by Yu, Zhu, Wang, and Zhang (1998).

TABLE 1
Results of the experimental study: ZY and the control group's performance

	Task	*ZY: correct %*	*Controls: correct % (SD)*
Visual comprehension			
Word	Similarity matching ($n = 121$)	90	90 (2)
	Verification ($n = 150$)	99	99 (1)
Arabic number	Similarity matching ($n = 111$)	95	96 (3)
	Verification ($n = 150$)	100	99 (1)
Auditory comprehension			
Word	Similarity matching ($n = 121$)	87	92 (2)
	Verification ($n = 150$)	97	98 (1)
Number	Similarity matching ($n = 111$)	44**	98 (1)
	Verification ($n = 150$)	83**	100 (0)
Written production			
Word	Writing-to-cues ($n = 30$)	47**	95 (4)
	Writing-to-dictation ($n = 42$)	14**	99 (1)
Arabic number	Writing-to-cues ($n = 30$)	100	100 (0)
	Writing-to-dictation ($n = 42$)	50**	100 (0)
Word number	Writing-to-cues ($n = 30$)	100	100 (1)
	Writing-to-dictation ($n = 42$)	40**	100 (0)

Note: **ZY performed significantly worse than controls in this task ($p < .001$); writing-to-dictation involves both auditory comprehension and written production.

Methods

Visual comprehension

Similarity matching. Each trial was presented on a sheet of paper, with the target item (word or Arabic number) on top and two candidate items (words or Arabic numbers) below. In the word trials, the subject judged which of the two bottom words (e.g., blanket, ice) was more closely associated with the target item (towel). In the number trial, he judged which of the two bottom numbers (e.g., 8, 2) was closer to the target in value (6). There are two sets of items for this task, each controlled for different psycholinguistic variables: *Set 1*: The target stimuli were matched on surface frequency (words mean: 0.8/thousand; numbers: 0.8/thousand; $t < 1$) and visual length (words: 1.81 characters; numbers: 1.89 digits; $t = 1.24$, $p = .22$); *Set 2*: The target stimuli were matched on syllable frequency (words mean: 0.8/thousand; numbers: 0.10/thousand; $t < 1$) and stimuli length (words mean: 2.23 characters; numbers: 2.42 digits; $t = 1.56$, $p = .12$).

Verification. In each trial a target word or Arabic number was presented along with one picture and the subject judged whether they matched by yes/no responses. For the word trials, one-third of the trials had a line drawing shown with a correct word, others with a word that was formally or semantically related to the picture name. Each number trial showed an Arabic digit and Chinese cash (RMB) with its number value covered up. One-third of the trials had the target digits matched the cash values (e.g., 20 with a cash of 20 RMB), others had the digits deviating from the cash value. The target words and target numbers were matched on surface frequency (words: 0.02/thousand; numbers: 0.02/thousand; $t < 1$) and visual length (words: 2 characters; numbers: 2 digits).

Auditory comprehension

These tasks were identical to the visual comprehension ones described above, except that the target stimuli were spoken to the subject by the experimenter.

Written production

In writing we had a chance to compare ZY's performances on (non-number) words, Arabic numbers, and word numbers and to better understand whether the dissociations we observed were between word/number categories (words vs. numbers, e.g., Butterworth et al., 2001; Caño et al., 2008; Marangolo et al., 2005) or between different scripts (Arabic script vs. verbal script, e.g., Cohen Kadosh et al., 2008).

Writing-to-cues. For target items, words were matched to word numbers by visual complexity (number of strokes, words: 5.47; word numbers: 6.00; $t = 1.34$, $p = .19$) and to Arabic numbers by frequency (words: 0.10/thousand; Arabic numbers: 0.10/thousand; $p = 1$). For word trial, the subject heard a compound word ('teapot') and was presented with a paper showing the first written character ('tea') followed by a blank, along with the object picture (teapot). He was instructed to write the second character ('pot') in the blank. For number trial, a written number (Arabic or word number) was presented and he was asked to write down the following number in the other number format (word number or Arabic).

Writing to dictation. This task involves both auditory input and written output. Words were matched with word numbers on number of strokes (words: 5.95; word numbers: 5.91; $t < 1$) and with Arabic numbers on frequency (words: 0.24/thousand; word numbers: 0.12/thousand; $t = 1.33$, $p = .19$). He was instructed to write down the words, word numbers or Arabic numbers that were spoken by the examiner.

Results

The patterns in the preliminary assessment were replicated here (see Table 1). In comparison to controls, ZY was normal in visual comprehension for both words (Matching task, overall, $p = 1$; Set 1, $p = .90$; Set 2, $p = .94$; Verification task, $p = 1$) and numbers ($ps > .5$ in all tasks). He was severely impaired in auditory comprehension for numbers ($ps < .0001$) and in written production of words ($t = -10.53$, $p < .0001$). Auditory comprehension of words ($ps > .05$) and written production (writing-to-cues) of numbers (Arabic numbers: $p = 1$; word numbers: $p = 1$) were preserved.

ZY showed significant dissociation between words and numbers in auditory comprehension ($ps < .001$) and in written production with the reverse pattern (i.e., writing-to-cue task: words vs. Arabic numbers: $x^2 = 42$, $p < .0001$; words vs. word numbers: $x^2 = 42$, $p < .0001$). In writing-to-dictation task he was impaired relative to controls for all stimuli type, and the difficulty for words was greater than for numbers (words vs. Arabic numbers: $x^2 = 12.28$, $p < .0001$; words vs. word numbers: $x^2 = 7.24$, $p < .01$).

A remaining issue for the above writing tasks is that, although we matched the surface frequency or visual complexity between words (e.g., 飞机, airplane) and numbers (e.g., 14/ 十四, fourteen), words' constituent characters (飞, 机) usually have lower frequency and/or higher visual complexity than the components of the number items (1, 4/ 十, 四). One may argue that the dissociation between Arabic/word numbers and words in these tasks could be attributed to superficial differences of such components. To inspect this possibility, we carried out a post hoc logistic regression analysis for the data in writing-to-cue – a relatively pure writing task. The dependent variable was the score of ZY's writing-to-cue result for a particular item (1 for correct and 0 for incorrect). The predictors were five relevant attributes of the item: (1) category (1 for word and 2 for Arabic/word number); (2) frequency of whole word/number; (3) mean frequency of components; (4) stroke number of whole word/number, and (5) mean stroke number of components. Our two-step hierarchical regression analyses revealed that after the effects of the confounding factors were removed, the dissociation (i.e., the unique contribution of 'category' to the writing performance) was still significant between words and numbers ($p = .02$) and between words and Arabic numbers ($p = .04$), and was marginally significant between words and word numbers ($p = .08$).

DISCUSSION

We documented a Chinese case with reverse patterns of dissociations between word and number processing across two modalities: ZY was better at words than numbers in auditory comprehension and better at numbers than words in written production. Furthermore, his writing performance of words was worse than both Arabic numbers and word numbers. His visual comprehension of both words and numbers was largely spared. He was equally impaired in the oral production of these two types of symbols, which might at least partly be attributed to the severe impairment of the articulatory system.

We argue that ZY's dissociations originated from the lexical processing stages in the auditory and written modalities because of the following reasons. First, his conceptual processing of words and numbers seemed to be largely spared, because he was at ceiling in visual comprehension tasks using the same items and comparable tasks as those in auditory comprehension. His selective number impairment in auditory comprehension was not readily attributed to pre-lexical auditory perception because his performances were not significantly different for words and numbers in a syllable perception task (words: 42/48; numbers: 47/48; $x^2 = 2.47$, $p > .1$), where he heard a syllable followed by a spoken target word or number and judged whether the word or number contained the target syllable. The observation that he was at ceiling in auditory lexical/number decision tasks for words and was at chance for numbers suggests that he was able to access the phonological lexical representations for words but not numbers. For written production, he was good at direct copying and delayed-copying of both words and numbers (all 100%), indicating that the post-lexical stages for writing, from the graphemic buffer to execution, were preserved. It is therefore inferred that his selective auditory number comprehension impairment was due to degraded phonological representations or failures to access intact ones or both; and his written word production impairment to the loss of orthographic (output) lexical representations or failures to access them or both. Moreover, the word–number dissociation in the written modality was along the categorical distinction, i.e., words versus numbers (Arabic numbers and word numbers), rather than along the script disparity (words/word numbers vs. Arabic numbers).

Is it possible that the dissociations we observed here were due to some nuisance variables? Different from the previously reported individuals with single dissociation between words and numbers (e.g., Anderson et al., 1990; Butterworth et al., 2001; Caño et al., 2008; Cappelletti et al., 2001; Cohen et al., 1997; Delazer et al., 2002; Marangolo et al., 2005), our current case showed reverse patterns of dissociation in two modalities. Therefore, a general task difficulty difference between words and numbers might not apply here. A more complex interaction between task difficulty and processing modality would have to be assumed. For instance, it may be argued that numbers rely more heavily on short term memory than words in the auditory comprehension modality, while words might be more visually complex than numbers in the written production modality. However, these variables do not readily account for the full pattern, because ZY showed comparable short term span for words and for numbers[1], and we controlled for variables such as lexical frequency, number of syllables, and visual/motoric complexity in the writing. Furthermore, for word numbers which are more similar to common words in orthography, ZY's writing skills were closer to those of Arabic numbers than to words. Our post hoc logistic regression analyses further ruled out the potential confounding effect of one other variable: the influence of the constituent components for compound words and numbers in the experimental items. We observed that the word–number dissociation effect still held after ruling out any contribution of frequencies and stroke numbers of whole words/numbers and their components. This result further consolidated that the word–number dissociation in ZY was not due to artifacts. One may notice the ZY's performances were not equivalent between the two writing tasks. For both types of numbers, he was perfect in writing-to-cue task (both 100% correct), and was impaired in writing-to-dictation (Arabic numbers: 50%; Word numbers: 40%). One likely reason for this discrepancy is that ZY had severe impairment in the auditory processing of numbers and his writing-to-dictation suffered from such difficulty in processing the auditory stimuli, while his writing-to-cue was not affected as no auditory processing was needed.

Unfortunately, while ZY presented a clear behavioral pattern in word and number distinction, his lesion profile, which involved almost the whole left hemisphere except the occipital lobe, does not allow us to establish a more precise anatomy–function correlation for the word and number processing across modalities.

To conclude, the case reported here showed double dissociations between word and number processing in the auditory comprehension and written production modalities. The word–number dissociation in writing was categorical (i.e., words vs.

[1]We specifically tested his short term memory spans for objects, words and digits in both auditory and visual modalities. He heard (for auditory) or saw (for visual) a series of object names, one-syllable words, or numbers, followed by a visual display of nine items (real objects, printed characters, or printed Arabic digits). He needed to point to the targets in the corresponding sequence (e.g., cup-scissors-watch for object sequence). His auditory short memory span and visual short memory span were equivalently impaired for the three stimuli types ($ps > .05$).

numbers) but not of script (i.e., Arabic vs. verbal). Such dissociations, we contend, originated from the lexical access stage in these two modalities, and could not be readily explained by nuisance variables such as processing difficulty. The finding reinforces the previously reported profiles that words and numbers are processed by segregated cognitive and neural mechanisms and suggests the universality of such segregation across languages.

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REFERENCES

Anderson, S. W., Damasio, A. R., & Damasio, H. (1990). Troubled letters but not numbers: Domain specific cognitive impairments following focal damage in frontal cortex. *Brain*, *113*, 749–766.

Butterworth, B., Cappelletti, M., & Kopelman, M. (2001). Category specificity in reading and writing: The case of number words. *Nature Neuroscience*, *4*, 784–785.

Caño, A., Rapp, B., Costa, A., & Juncadella, M. (2008). Deafness for the meanings of number words. *Neuropsychologia*, *46*(1), 63–81.

Cipolotti, L., Butterworth, B., & Denes, G. (1991). A specific deficit for numbers in a case of dense acalculia. *Brain*, *114*, 2619–2637.

Cohen, L., Verstichel, P., & Dehaene, S. (1997). Neologistic jargon sparing numbers: A category-specific phonological impairment. *Cognitive Neuropsychology*, *14*, 1029–1061.

Cohen, L., Dehaene, S., Cohochon, F., Lehéricy, S., & Naccache, L. (2000). Language and calculation within the parietal lobe: A combined cognitive, anatomical and fMRI study. *Neuropsychologia*, *38*, 1426–1440.

Cohen Kadosh, R. C., Henik, A., & Rubinsten, O. (2008). Are Arabic and verbal numbers processed in different ways? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *34*, 1377–1391.

Crawford, J. R., & Garthwaite, P. H. (2005). Testing for suspected impairments and dissociations in single-case studies in neuropsychology: Evaluation of alternatives using Monte Carlo simulations and revised tests for dissociations. *Neuropsychology*, *19*, 318–331.

Crawford, J. R., & Garthwaite, P. H. (2007). Comparison of a single case to a control or normative sample in neuropsychology: Development of a Bayesian approach. *Cognitive Neuropsychology*, *24*, 343–372.

Delazer, M., Lochy, A., Jenner, C., Domahs, F., & Benke, T. (2002). When writing 0 (zero) is easier than writing O (o): A neuropsychological case study of agraphia. *Neuropsychologia*, *40*(12), 2167–2177.

Marangolo, P., Piras, F., & Fias, W. (2005). 'I can write seven but I can't say it': A case of domain-specific phonological output deficit for numbers. *Neuropsychologia*, *43*, 1177–1188.

Messina, G., Denes, G., & Basso, A. (2009). Word and number transcoding: A retrospective study on 57 aphasic subjects. *Journal of Neurolinguistics*, *22*, 486–494.

Thioux, M., Pillon, A., Samson, D., de Partz, M.-P., Noël, M.-P., & Seron, X. (1998). The isolation of numerals at the semantic level. *Neurocase*, *4*, 371–389.

Yu, S., Zhu, X., Wang, H., & Zhang, Y. (1998). *The grammatical knowledge-base of contemporary Chinese: A complete specification*. Beijing, China: Tsinghua University Press.