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Phonological activation improves semantic access provided by Arabic digits and number words

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Abstract

Arabic digits (e.g., "6") and number words (e.g., "六", "six", "༦") are the two main formats in which numbers can be represented. Although phonology plays a crucial role in the semantic accessing of alphabetic words and Chinese characters, whether it is involved in the processing of different numerical notations, which have been shown to be dissociable from characters, is still unknown. Using a parity judgment task, two experiments were performed by manipulating the phonological relationship between a prime and a target. The primes were Tibetan or Chinese characters and the targets were presented either as number words (Experiment 1) or as Arabic digits (Experiment 2). The results revealed that phonology affected semantic access for both number words and Arabic digits. Additionally, semantic access for Tibetan number words was more susceptible to phonological information. The results for Arabic digits followed the same pattern for Tibetan primes. Further, language proficiency also affected the role of phonology in number processing. Participants with low language proficiency relied more on phonological encoding when processing the numbers. The results suggest that phonology is crucial for semantic access of different numerical notations.

Keywords Number processing · Phonology · Semantic access · Tibetan-Chinese bilinguals · Language proficiency

Introduction

When we hear the word "number," when we perform calculations, or when we buy something, we often see, use, or think of Arabic digits. However, numbers are also notated as a linguistic format, which are called number words (e.g., "六", "six", "sechs", "༦"). A substantial body of research in the field of numerical cognition has been investigating the processing similarities and differences between Arabic digits and number words (Campbell & Clark, 1988; Cipolotti & Butterworth, 1995; Damian, 2004; Dehaene & Cohen, 1995, 1997; Fias, 2001; Fias, Reynvoet & Brysbaert, 2001; Herrera & Macizo, 2011, 2012; Macizo & Álvarez, 2018; McCloskey, 1992; Sella & Cohen Kardosh, 2018). Some authors have reported that access to semantic representation is faster and more automatic for Arabic digits than for number words (Damian, 2004; Fias, 2001; Fias et al., 1996). However, some evidence supports an asemantic route connecting Arabic digit input to phonological information (Dehaene, 1992). Thus, whether or not phonological information is activated by Arabic digits and number words is a question still being debated. The current study used a phonological priming effect to examine the role of phonology in the semantic access of number words and Arabic digits.

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Processing routes for Arabic digits and number words

Arabic digits do not have a universal phonological code and their visual forms relate to many phonological forms depending on the language currently in use. For example, "5" can be coded in many ways. In an ideographic written system such as Chinese, it has a single written form, which is similar to the Arabic digit (i.e., "五") and its phonology can only be [wǔ]. In an alphabetical system such as English, the written form is the word "five," which consists of several letters, and its phonology can only be [faɪv]. These numbers express exactly the same quantitative information. In this study, we are interested in how we represent these different formats of numbers and whether we use different pathways to access the different number notations.

Previous studies have investigated Arabic digits and number words, showing that these two number notations are processed in different ways (Campbell et al., 1999; Carreiras et al., 2015; Cohen et al., 2008; Damian, 2004; Dehaene et al.,1993; Fias, 2001; Ito & Hatta, 2004; Sella & Cohen, 2018; Smith & Magee, 1980). Studies have found that Arabic digits are processed faster than number words in numerical and magnitude judgment tasks and in simple addition and multiplication tasks (Campbell et al., 1999; Damian, 2004). However, some studies have found that Arabic digits are not always processed faster than number words (Campbell & Epp, 2004; Damian, 2004; Dong, 2007; Wu, 2011). For instance, in a naming task, Damian (2004) examined processing differences between two notational formats and found that number words were named faster than corresponding Arabic digits. Also using a number naming task, Campbell and Epp (2004) found that processing speed did not differ between Mandarin number words and Arabic digits. Thus, processing appears to be asymmetric; in naming tasks, number words are processed faster than digits, while in magnitude judgment tasks or multiplication tasks, Arabic digits are processed faster.

One reason for this asymmetric processing seems to depend on whether or not the semantic information (numerical value) needs to be activated in the experimental task. Specifically, when we read number words aloud, the orthographic information can be transformed into phonemes without needing to access the meaning. For tasks that require semantic information (e.g., parity judgment tasks), access to that information is obtained through the visual form (reading). In contrast, the semantic information of Arabic digits can be accessed directly without activating phonological codes, the processing of which is most likely similar to object recognition. If this is the case, it is not surprising that Arabic digits are processed faster than number words in tasks that require semantic information, while number words are processed faster in naming tasks. In fact, several researchers theorize a semantic route for processing Arabic digits (Damian, 2004; Fias, 2001; Fias et al., 1996; Ito & Hatta, 2004), in which Arabic digits have fast and automatic access to semantic information.

Nevertheless, evidence from neuropsychological studies supports an alternative asemantic route through which Arabic digits are processed (Cipolotti & Butterworth, 1995; Dehaene & Cohen, 1997; Sokol & McCloskey, 1988). In Dehaene and Cohen (1997), the authors instructed two brain-impaired patients with good performance on an Arabic digit-naming task to judge the magnitudes of two digits, and results showed this ability was substantially impaired. This indicates that processing Arabic digits and number words could be similar; both types of number notation appeared to be transformed into verbal codes without gaining access to the semantic information. Arabic digits are assumed to be processed much the way objects are, with semantics accessed directly as they are in picture naming (Damian, 2004; Fias, 2001; Fias et al., 2001; McCloskey, 1992). However, considering that Arabic digits are also a type of special language, rather than just ordinary objects, their phonological codes are most likely activated as they are processed. Indeed, several studies propose that, similar to word naming, Arabic digits are processed through an asemantic route (Campbell & Clark, 1988; Cipolotti & Butterworth, 1995; Dehaene, 1992; Roelofs, 2006; Herrera & Macizo, 2012). Herrera and Macizo (2012) provided evidence suggesting that Arabic digits are named through an asemantic route similar to that of number words. Furthermore, new evidence from neuropsychological studies suggests that access to phonological information might begin in parallel with semantic processing during the picture-naming task (Miozzo et al., 2015; Strijkers et al., 2017). Accordingly, if phonological information can be activated like semantic information, it's worth examining the role of phonological codes in the process of Arabic digits and number words.

Phonological activation during the word recognition

The role of phonology has always been an important issue in the field of language comprehension (Leck et al., 1995; Rayner et al., 1998; Rubenstein et al., 1971; Seidenberg, 1985; Taft & van Graan 1998). Three models have been proposed to explain access to word meaning: the Direct Access theory, the Phonological Mediation theory, and the Dual Route theory. According to the Direct Access theory (Leck et al., 1995; Taft & van Graan, 1998), a word's semantic information is directly accessible through its orthography, and the activation of phonological information is an additional process that occurs after the semantics have been accessed. In contrast, the Phonological Mediation theory says that phonological information plays an important and intermediary role in the process of semantic access, with the phonological code being transformed from the orthography at the start (Rayner et al., 1998; Rubenstein et al., 1971; Luo, 1996). The debate between these two theories focuses on whether phonology can be activated automatically via visual word recognition (Perfetti & Harris, 2013). According to the

Dual Route theory, two pathways exist simultaneously and are both activated when we recognize a visual word (Kay & Ellis, 1987; Seidenberg, 1985). An interesting finding is that in ideographic written systems such as Chinese, access to semantic knowledge is gained directly without activating the phonology (Taft & van Graan, 1998; Zhou et al., 1999), while in alphabetic systems, phonology is mainly used as an intermediary in acquiring semantic information. From the perspective of language processing, both number words and Arabic digits are composed of orthographic, phonological, and semantic information. Therefore, whether phonological information is activated when processing Arabic digits and number words could depend on the writing system.

The current study

Although past studies have focused on the semantic or asemantic pathway for processing different types of numeral notation, the tasks that they used can only indirectly infer the pathway. Few experiments have directly manipulated phonology (asemantic route). To explore whether phonology plays a role in processing Arabic digits or number words more directly, we used a priming paradigm to manipulate the phonological relationship between the prime and target. Instead of carrying out a semantic judgment task (living/non-living things) in the priming paradigm, participants made a parity judgment task in the current study, which also requires access to the semantic information of numbers (Dehaene, Bossini & Giraux, 1993; Fias et al., 1996; Fias et al., 2001; Reynvoet & Brysbaert, 1999; Winskel & Ratitamkul, 2021). Thus, participants made parity judgments by accessing number values, rather than performing a task in terms of phonological activation.

Moreover, we recruited Tibetan-Chinese bilinguals who master at least three different numeral systems: Tibetan number words from an alphabetic writing system, Chinese number words from an ideographic writing system, and the numeral system of Arabic digits. Even though number processing studies found that we can access Arabic digits without activating the phonology, other studies found that processing for these two notations was symmetrical. Additionally, according to language processing models for the alphabetic writing system, phonology should be activated if the Arabic digits are regarded as a special type of text. Considering that language proficiency is also an important factor affecting semantic access, a more complicated situation is predicted for processing Arabic digits. For example, Winskel and Ratitamkul (2021) investigated the processing of numerical digits and words in Thai-English bilinguals and found that proficiency in the second language likely modulates the interference effect during the number processing. Thus, the present study also divided the participants into high and low Chinese-proficiency groups to investigate this question in more detail.

Two issues are addressed in the current study. First, we sought to determine whether a phonological pathway exists for processing number words and Arabic digits. Are there processing differences between these two types of notations? Second, how does language proficiency impact the processing? Unlike previous studies, the current study manipulated the phonology directly. Whether we treat Arabic digits as a special type of words or objects, its phonology is expected to be activated before or parallel with its meaning. On the contrary, if Arabic digits can be accessed in a semantic route (Campbell et al., 1999; Damian, 2004), we would not observe the phonological activation during the semantic access. For the number words, as a type of alphabetic character, the phonology of Tibetan number words' phonology should be activated during the semantic access based on the Phonological Mediation theory. However, according to the results that phonology is not activated during Chinese word recognition (Taft & van Graan, 1998; Zhou et al., 1999; Zhou & Marslen-Wilson, 2000), we predicted the Chinese number-number word might be accessed without phonology activation. But it may depend on the Chinese proficiency of the bilinguals. Participants with low language proficiency would be affected more by phonology than those with high language proficiency. Therefore, we predicted that phonology would be activated during number processing, and Tibetan number words would be affected more by phonology than Arabic digits or Chinese number words. In addition, language proficiency might have an impact on the number processing for the Tibetan-Chinese bilinguals.

Experiment 1

Experiment 1 was designed to explore whether a phonological pathway exists for processing Tibetan and Chinese number words in Tibetan-Chinese bilinguals. First, to address the influence of language proficiency on number processing, the language-proficiency level was manipulated between groups (i.e., high- and low-language proficiency levels). Second, by manipulating the phonological relationship between the prime and target in a priming paradigm, we were able to test whether the phonological information activates as the participants make a parity judgment task to access the meaning of the target number words. Several hypotheses were posed. (1) The activation of the phonological information is predicted to be shown both in the processing of Tibetan and Chinese number words. Thus, the participants should be faster and more accurate when the prime and target were homophones. (2) There are processing differences between Chinese and Tibetan words (Taft & van Graan, 1998; Zhou et al., 1999). (3) Language proficiency is expected to affect number processing (Winskel & Ratitamkul, 2021).

Methods

Participants

We used G*Power 3.1 developed by Faul et al. (2009) to determine participant numbers. The current study adopted a within-between interaction design and we set the effect size to 0.25 and α error probability to 0.05. The power reached 0.95 when the number of participants was 72. Hence, 81 Tibetan-Chinese bilinguals (more than 72) who were native Tibetan and spoke Chinese as a second language (males = 39 and 42 females, average age = 15.75 years, SD = 0.81) were selected from an ethnic college in Hebei. They were right-handed and had a normal or corrected-to-normal vision.

Adopting the way of proficiency assessment by Paolieri et al. (2020), participants' Chinese proficiency was assessed by a five-point scale, in which "5" stood for a very proficient level. In the assessment, the instruction for "5" presented to the participants was "Five means you are entirely fluent in a language. You were raised using the language or have used it long enough to become proficient in it. No one else realizes or barely realizes that this is your second language." The instruction for "1" was "One means that knowledge of the language is limited to a few words." According to the results of the assessment, they were divided into two groups: high (n = 41; 22 males and 19 females) and low (n = 40; 17 males and 23 females) language proficiency. The average Chinese proficiencies for high and low language-proficiency groups were 4.27 (SD = 0.34) and 3.54 (SD = 0.36), respectively. An independent-sample *t*-test showed a significant difference in Chinese proficiency between the two groups (t = 9.42, p < .001). Specifically, participant abilities for listening, reading, speaking, and writing Chinese are shown in Table 1. Individually, listening, reading, speaking, and writing skills were all greater in the high language proficiency group than in the low language proficiency group ($t_l = 6.49$, $t_r = 7.75$, $t_s = 6.31$, $t_w = 5.18$, all *ps* < .001). Before the experiment, participants did not know the purpose of the experiment. After completing the experiment, they were rewarded accordingly.

Table 1 Chinese ability in Tibetan-Chinese bilinguals from Experiment 1

Language ability	High proficiency group	Low proficiency group
Listening	4.51	3.83
Reading	4.34	3.45
Speaking	4.39	3.68
Writing	3.85	3.20

Apparatus

E-Prime 3.0 software from Psychology Software Tools was used to program and present the experimental stimuli and collect the data. Display resolution for the computer was 1,024 × 768 pixels. Participants were seated about 70 cm away from the 17-in. (43.18 cm) screen.

Stimuli and design

Using a priming paradigm, we constructed a 2 (priming type: priming vs. non-priming) × 2 (number-word type: Tibetan vs. Chinese) × 2 (language proficiency: high vs. low) experimental design. The materials were divided into phonological priming or non-priming primes (Tibetan or Chinese words) and targets (Tibetan and Chinese number words). Phonological relation between the primes and targets was manipulated. The priming words and target number words were homophones in the priming condition and had different pronunciations in the non-priming condition. For example, for Chinese word type, the prime (e.g., "午", /wu3/, meaning *noon*) had the same pronunciation as the target (e.g., "五", /wu3/, meaning *five*) in the priming condition, while the prime "由" (/you2/, meaning *reason*) had a different pronunciation from the target "五" in the non-priming condition. For the Tibetan word type, the prime (e.g., "རྔ་", /nga/, meaning *drum*) had the same pronunciation as the target (e.g., "༥", /nga/ meaning *five*) in the priming condition, while the prime "རི་" (/ri/, meaning *mountain*) had a different pronunciation in the non-priming condition. Participants were to perform a parity judgment task (whether the given target word is odd or even) rather than a phonological task in the paradigm.

For the phonological primes, we chose 56 Chinese characters from the "Xinhua Dictionary" and 56 Tibetan characters from the "Tibetan-Chinese Dictionary." Half of each language set were homophones for the number words and the other half has different pronunciations. The selection criteria for words with different phonologies were that they had high usage frequencies, and semantics that did not include quantitative information. A five-point scale was used to evaluate the familiarity of the selected words, in which "1" stands for very unfamiliar and "5" stands for very familiar. After evaluation, Tibetan and Chinese words with familiarity lower than 4.6 were removed. We also balanced the number of strokes between the Chinese characters and the length of the Tibetan characters. Finally, we selected 40 characters (half Chinese, half Tibetan) as the phonological primes. The results of the familiarity self-assessment can be found in Table 2.

We used a *t*-test to assess differences in familiarity and the number of strokes (or word length) and found that the Chinese words and Tibetan words were not significantly different (t = 1.85, p >.05). For the Chinese priming words,

Table 2 Evaluation for priming selection

	Chinese prime word		Tibetan prime word	
	Priming	Non-priming	Priming	Non-priming
Familiarity	4.79 (0.05)	4.82 (0.07)	4.84(0.06)	4.85(0.07)
Word length	6.80 (1.98)	6.20 (1.39)	2.40(0.50)	2.60(0.50)

Values in parentheses are standard deviations

t-tests for the familiarity of the characters and the number of strokes showed no significant differences between the number-word homophones and non-homophones for familiarity (t = 1.02, p > .05) and for the number of strokes (t = 0.78, p > .05). For the Tibetan priming words, *t*-tests were performed on the familiarity and word length of the Tibetan words. The results showed no difference for familiarity (t = 0.39, p >.05) or word length (t = 0.87, p > .05). For target words, given that there are no more homophone corresponding to the number words, seven Tibetan number words (༡, ༢, ༣, ༤, ༥, ༧, ༨which correspond to 1, 2, 3, 4, 5, 7, 8) and Chinese number words (一, 四, 五, 六, 七, 八, 九, which correspond to 1, 4, 5, 6, 7, 8, 9) were selected.

Thus, the selected experimental materials were divided into four types to construct four conditions: Chinese phonologically consistent word pairs (Chinese priming condition), Chinese phonologically inconsistent word pairs (Chinese non-priming condition), Tibetan phonologically consistent word pairs (Tibetan priming condition), and Tibetan phonologically inconsistent word pairs (Tibetan non-priming condition). The word pairs were balanced and repeated three times in each condition in a random order.

Procedure

First, participants were required to read the instructions. They became familiar with the experimental contents and procedures during a practice phase. When the experimental trials began, a 300-ms red fixation cross was displayed in the center of the screen. Participants were then presented with a 500-ms prime (Chinese or Tibetan character) and then a 1,500-ms target number word. They were instructed to judge whether the target number was odd or even, by pressing the "F" or "J" keys, respectively. The key pressed for the odd and even in the experiment was balanced. Participants were required to respond as soon as possible. If they did not respond within 1,500 ms, the target number words disappeared and the next trial began. In the practice stage, participants received feedback indicating whether their choice was correct or not. The experimental trials did not have feedback. The experimental procedure is shown in Fig. 1.

Transparency and openness

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. All data, analysis code, and research materials are available upon reasonable request from the corresponding authors.

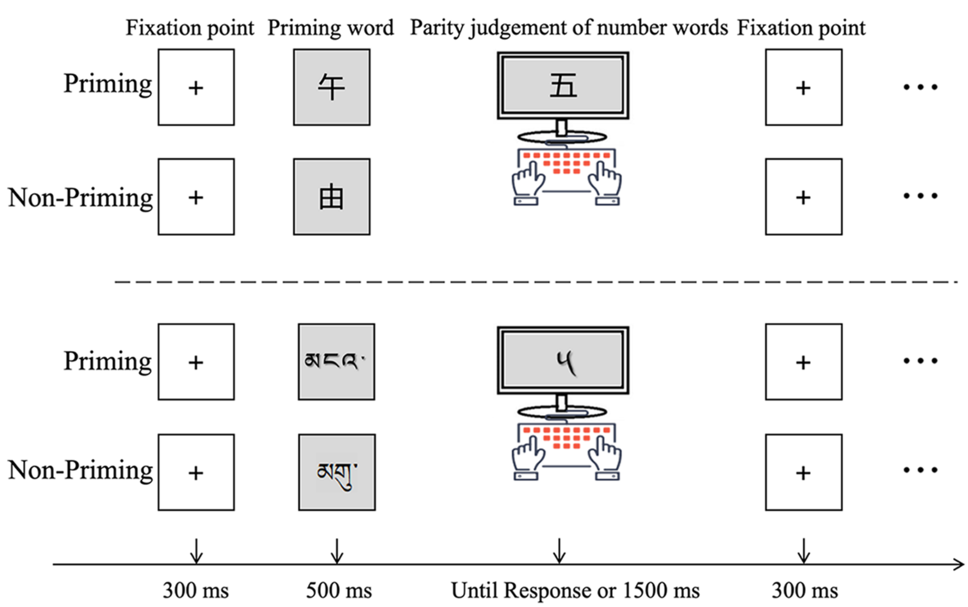

Fig. 1 Procedure used in Experiment 1. The upper section shows the Chinese priming condition and the lower section shows the Tibetan priming condition

Data were analyzed using IBM SPSS, version 24.0. This study's design and its analysis were not pre-registered.

Results

Before analyzing the data, we excluded trials in which the reaction time was beyond 3 standard deviations from the mean (two trials were excluded), and trials in which the error rate was beyond 3 standard deviations from the mean (four trials were excluded), resulting in a loss of 0.7% of the data. Then, the data were analyzed by IBM SPSS 24.0. The results of response time were shown in Table 3 and Fig. 2. The results of error rates were shown in Table 4 and Fig. 3.

Repeated-measure analysis of variance (ANOVA) revealed significant main effects of number type ($F_{(1,73)}$ = 85.14, $p < .01$, $\eta^2 = 0.538$) and priming type ($F_{(1,73)}$ = 261.20, $p < .01$, $\eta^2 = 0.782$) on reaction time. We also found a significant interaction between the two factors ($F_{(1,73)}$ = 34.91, $p < .01$, $\eta^2 = 0.324$), and further analysis showed that for Chinese number words, the difference between the priming (505.19 ms) and non-priming (611.02 ms) conditions was significant (difference = 105.83 ms, $p < .01$, $\eta^2 = 0.671$). For Tibetan number words, reaction times also differed between priming (588.00 ms) and non-priming (773.31 ms) conditions (difference =185.31 ms, $p < .01$, $\eta^2 = 0.726$). The difference in reaction time was greater for Tibetan number words than for Chinese number words.

The interaction between priming type and language proficiency was also significant ($F_{(1,73)}$ = 4.493, $p < .05$, η^2 = 0.058). Further analysis showed that reaction times for the high language-proficiency group differed significantly between priming (536.19 ms) and non-priming (662.66 ms) conditions ($p < .01$, $\eta^2 = 0.006$). The difference between priming (557.01 ms) and non-priming (721.66 ms) conditions in the low language-proficiency group was larger than that for the high language-proficiency group, and also significant ($p < .01$, $\eta^2 = 0.688$).

Table 3 Response time for parity judgment in Experiment 1 (ms)

Language proficiency		High language proficiency		Low language proficiency	
Number words type		Chinese	Tibetan	Chinese	Tibetan
Priming Type	Priming	490.47 (111.75)	581.91 (181.17)	519.92 (124.92)	594.10 (191.31)
	Non-priming	583.12 (90.00)	742.21 (141.68)	638.92 (112.85)	804.41 (174.27)

Values in parentheses are standard deviations

Table 4 Error rates for the parity judgments in Experiment 1 (%)

Language proficiency		High language proficiency		Low language proficiency	
Number words type		Chinese	Tibetan	Chinese	Tibetan
Priming type	Priming	3.87 (3.93)	6.72 (5.93)	5.53 (4.75)	8.33 (7.49)
	Non-priming	4.59 (5.30)	10.44 (7.35)	5.19 (4.35)	13.72 (9.22)

Values in parentheses are standard deviations

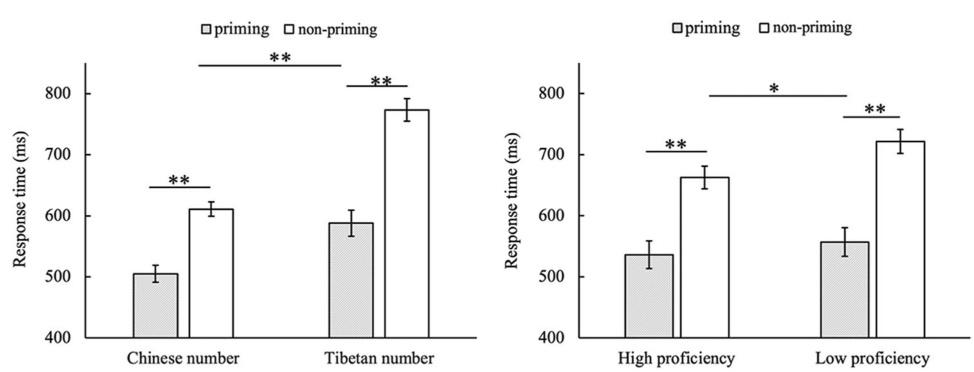

Fig. 2 Response times for the parity judgments in Experiment 1

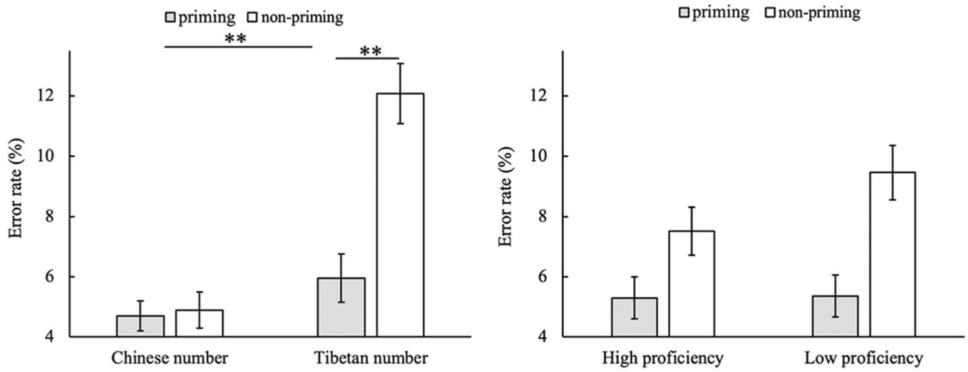

Fig. 3 Error rates for the parity judgments in Experiment 1

We also used a repeated-measures analysis of variance (ANOVA) for error rates, finding significant main effects of the number type ($F_{(1,73)} = 51.85$, $p < .01$, $\eta^2 = 0.415$) and priming type ($F_{(1,73)} = 14.65$, $p < .01$, $\eta^2 = 0.167$). The interaction between the two factors was also significant. Further analysis found that when judging Chinese number words, the difference in error rate between the priming condition (4.7%) and the non-priming (4.9%) conditions was non-significant (0.2%; $p > .05$, $\eta^2 = 0.001$). However, when judging Tibetan number words, the error rate in the priming condition (7.5%) was significantly lower than that in the non-priming condition (12.1%; difference = 4.6%, $p < .01$, $\eta^2 = 0.203$).

As is evident from the results, for Tibetan-Chinese bilinguals, both Tibetan number words and Chinese number words were affected by the activation of phonological information during the semantic processing of number words. The activation of Tibetan phonology promoted the processing of Tibetan number words, and the activation of Chinese phonology promoted the processing of Chinese number words. The interaction between priming type and number type for both response time and error rate showed that the priming effect was greater for Tibetan number words than for Chinese number words, indicating that Tibetan number words, which are alphabetic, were more sensitive to phonological priming. In addition, the interaction between priming type and language proficiency showed that phonology had a greater impact on participants with low-language proficiency than on participants with high-language proficiency.

Experiment 2

Experiment 1 investigated whether phonology plays a role in the semantic access of Tibetan and Chinese number words, and it was found that phonology promoted the processing of both types of number words. The purpose of Experiment 2 was to test the first question in the introduction, that is, whether a phonological pathway also exists in the semantic access of Arabic digits in Tibetan-Chinese bilinguals. Similarly, the influence of second language proficiency on number processing was also investigated by dividing the participants into high- and low-proficiency levels. Because Arabic digits can be pronounced two ways for Tibetan-Chinese bilinguals (i.e., in their native Tibetan and their second language Chinese), the primes include Tibetan words and Chinese words, and the target word is Arabic digits in both priming types.

Most importantly, Experiment 2 was also designed to examine the processing differences between number words and Arabic digits by comparing the results of the two experiments. Processing Arabic digits has been shown to be different from processing number words (e.g., Damian, 2004; Fias, 2001; Fias et al., 1996; Ito & Hatta, 2004). Yet some studies have shown that the processing of Arabic digits is similar to the processing of number words (Cipolotti & Butterworth, 1995; Dehaene & Cohen, 1997; Sokol & McCloskey, 1988). We expected to find phonology activation in the semantic access of Arabic digits (Herrera & Macizo, 2012; Miozzo et al., 2015; Strijkers et al., 2017).

Methods

Participants

Eighty-three Tibetan-Chinese bilinguals (38 males and 45 females, average age = 15.69 years, SD = 0.81) were recruited from an ethnic college in Hebei. Participants had not participated in Experiment 1 or any other psychological experiment before. They were all right-handed and had a normal or corrected-to-normal vision. According to the results of the Chinese proficiency assessment, they were divided into two language-proficiency groups: high (n = 44; 22 males and 22 females) and low (n = 39; 16 males and 23 females). The language ability of the participants is shown in Table 5. The difference in average Chinese proficiencies between the high and low language proficiency groups was significant (high:

Table 5 Chinese listening, speaking, reading, and writing skills in Experiment 2

Language ability	High proficiency group	Low proficiency group
Listening	4.55	3.82
Reading	4.41	3.44
Speaking	4.45	3.69
Writing	3.93	3.18

4.34, SD = 0.37; low: 3.53, SD = 0.37, t= 9.90, p < .01). The Chinese listening, reading, speaking, and writing skills for the high language-proficiency group were all higher than those for the low language-proficiency group (t-test; $t_l = 6.92$, $t_r = 8.45$, $t_s = 6.77$, $t_w = 5.98$, all $ps < 0.001$).

Apparatus, stimuli, and design

Experiment 2 adopted a 2 (priming type: priming vs. non-priming) × 2 (priming-word type: Tibetan vs. Chinese) × 2 (language proficiency: high vs. low) design. The primes included Tibetan and Chinese words, which were the same as in Experiment 1; while the targets were single Arabic digits rather than number words, which corresponded to the target number words in Experiment 1. Thus, there were seven Arabic digits (1, 2, 3, 4, 5, 7, 8, which correspond to the Tibetan number words used in Experiment 1,༡, ༢, ༣, ༤, ༥, ༧, ༨) in Tibetan priming conditions and seven Arabic digits (1, 4, 5, 6, 7, 8, 9, which correspond to the Chinese number words used in Experiment, 一, 四, 五, 六, 七, 八, 九,) in Chinese priming conditions. The Chinese priming words (e.g., “午”, /wu3/, meaning *noon*) had the same pronunciation as the Chinese pronunciation of Arabic digits (e.g., 5) in the priming condition, while the prime “由” (/you2/, meaning *reason*) had a different pronunciation from the Arabic digit “5” in the non-priming condition. Similarly, the Tibetan priming words had the same pronunciation as the Tibetan pronunciation of Arabic digits in the priming condition, while the prime had a different pronunciation from the Arabic digit in the non-priming condition. Thus, in both proficiency groups, we had four conditions: Chinese priming condition, Chinese non-priming condition, Tibetan priming condition, and Tibetan non-priming condition. The apparatus was the same as in Experiment 1.

Procedure

The experimental process was basically the same as in Experiment 1, aside from the difference in target stimuli. First, a 300-ms red fixation cross was displayed in the center of the screen. Participants were then presented with a 500-ms prime (Chinese or Tibetan character) and then a 1,500-ms Arabic digit. They were instructed to judge whether the Arabic digit was odd or even, by pressing the “F” or “J” keys, respectively. The key pressed for the odd and even in the experiment was balanced. Participants were required to respond as soon as possible. If they did not respond within 1,500 ms, the target Arabic digits disappeared and the next trial began. In the practice stage, participants received feedback indicating whether their choice was correct or not. The experimental trials did not have feedback. The experimental procedure is shown in Fig. 4.

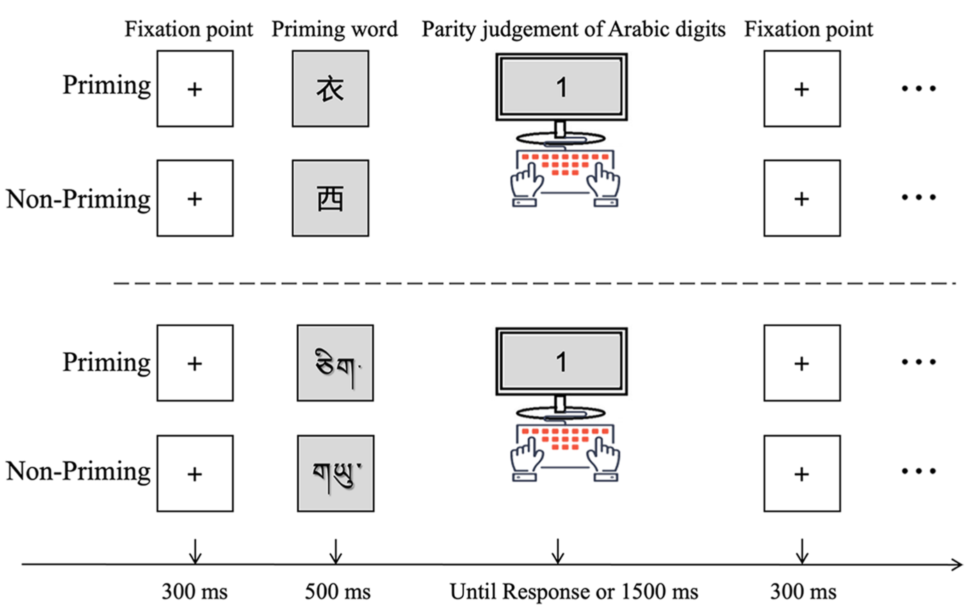

Fig. 4 The procedure used in Experiment 2. The upper section shows the Chinese priming condition and the lower section shows the Tibetan priming condition

Table 6 Response times for the parity judgments in Experiment 2 (ms)

Language proficiency		High language proficiency		Low language proficiency	
Priming-word type		Chinese	Tibetan	Chinese	Tibetan
Priming type	Priming	594.89 (109.23)	575.29 (110.69)	659.24 (144.96)	635.55 (154.45)
	Non-priming	663.15 (103.15)	656.08 (112.65)	715.28 (158.76)	706.68 (151.87)

Values in parentheses are standard deviations

Transparency and openness

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study. All data, analysis code, and research materials are available upon reasonable request from the corresponding authors. Data were analyzed using IBM SPSS, version 24.0. This study's design and its analysis were not pre-registered.

Results

Before analyzing the data, we excluded trials in which the reaction time was beyond 3 standard deviations from the mean (one trial was eliminated), and trials in which the error rate was beyond 3 standard deviations from the mean (four were eliminated), resulting in a loss of 0.6% of the data. Then, the data were analyzed by SPSS 24.0. The results of response time were shown in Table 6 and Fig. 5. The results of error rates were shown in Table 7 and Fig. 6.

Repeated-measure analysis of variance (ANOVA) revealed significant main effects of priming-word type ($F_{(1,76)}$ =7.52, $p < .01$, $\eta^2 = 0.09$), priming type ($F_{(1,76)}$ = 58.99, $p < .001$, $\eta^2 = 0.44$), and language proficiency ($F_{(1,76)}$ = 4.36, $p < .05$, $\eta^2 = 0.054$) on reaction time. However, we found no significant interactions.

Repeated-measure analysis of variance (ANOVA) also revealed significant main effects of priming-word type ($F_{(1,76)} = 4.70$, $p < .05$, $\eta^2 = 0.058$) and priming type ($F_{(1,76)}$ = 9.88, $p < .01$, $\eta^2 = 0.115$) on error rate. The interaction between priming-word type and priming type was also significant. Further analysis found that the difference in error rate between the priming condition (7.0 %) and the non-priming condition (6.4%) was not significant when the primes were Chinese characters ($F(_{1,76)} = 0.901$, $p = 0.345$, $\eta^2 = 0.012$). However, when the primes were Tibetan words, the error rate was significantly lower in the priming condition (5.7%) than in the non-priming condition (10.5%; $F_{(1,76)}$ = 23.62, $p < .001$, $\eta^2 = 0.237$).

A marginally significant interaction between priming type and language proficiency was also found ($F_{(1,76)} = 3.70$, p = 0.058, $\eta^2 = 0.046$). Further analysis showed no significant difference between the priming (6.30%) and the non-priming (7.00%) conditions in the high language-proficiency group ($F_{(1,76)} = 0.83$, $p = 0.366$, $\eta^2 = 0.011$). However, for the low language proficiency group, the interaction was significant (priming: 6.50%; non-priming: 9.80%; $F_{(1,76)} = 11.65$, p = 0.001, $\eta^2 = 0.133$).

According to the reaction time results in Experiment 2, both Tibetan and Chinese primes that correspond to Arabic digits had significant priming effects on the target digits, thus promoting the semantic processing of Arabic digits. Additionally, the interaction between priming-word type and priming type on response time was similar to what we observed in Experiment 1. Compared with Chinese words, Tibetan characters that have a phonological relationship with Arabic digits influenced reaction time, and more obviously error rate on the parity judgment task. Second language proficiency also affected the degree to which phonology could impact semantic processing.

General discussion

In the current study, two experiments were conducted using a priming paradigm to investigate whether phonological information can impact the processing of number words or Arabic digits. For the number words, we found that parity

Table 7 Error rates for the parity judgments in Experiment 2 (%)

Language proficiency		High language proficiency		Low language proficiency	
Priming-word type		Chinese	Tibetan	Chinese	Tibetan
Priming type	Priming	6.44 (6.26)	6.07 (5.18)	7.66 (6.38)	5.40 (5.63)
	Non-priming	4.70 (5.22)	9.40 (7.93)	8.03 (7.51)	11.60 (8.47)

Values in parentheses are standard deviations

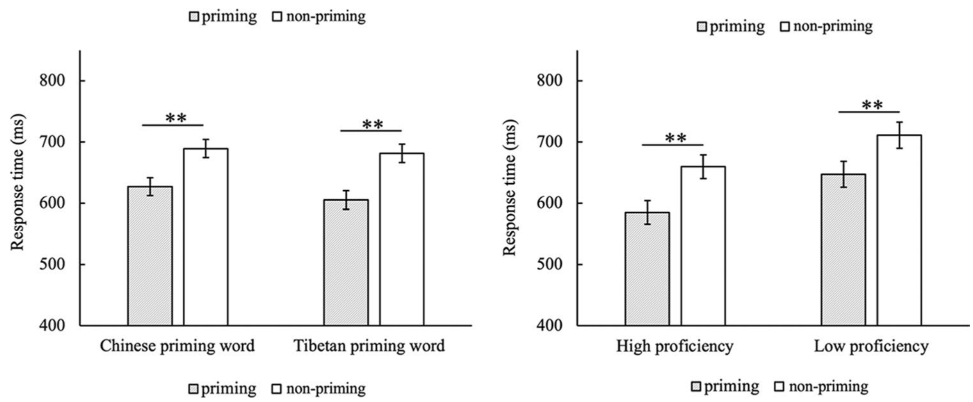

Fig. 5 Response times for the parity judgments in Experiment 2

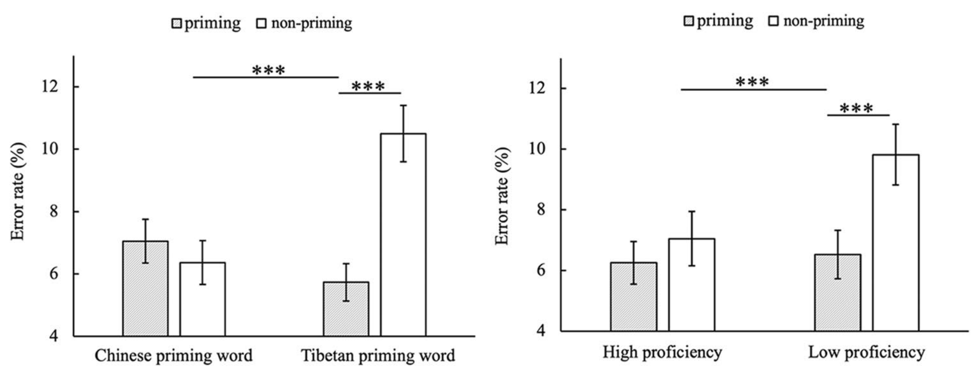

Fig. 6 Error rates for the parity judgments in Experiment 2

judgments of both Tibetan and Chinese number words could be primed by the phonological relationship between priming and target. Thus, Tibetan and Chinese number words were processed faster in the phonological priming condition, as measured by the response time of parity judgment. In addition, the phonological priming effect for Tibetan number words was significantly greater than that of Chinese number words, showing a stronger phonological mediating pathway for the alphabetic Tibetan number words. Interestingly, we also found a priming effect of phonology on Arabic digits in a parity judgment task that requires semantic knowledge, but not phonological coding. Additionally, the alphabetic mother tongue (i.e., Tibetan) rather than the ideographic second language (i.e., Chinese) influenced the processing of Arabic digits. Thus, language proficiency plays an important role in phonological priming when processing numbers.

Phonological activation during the processing of number words and Arabic digits

The results of Experiment 1 showed that number words were judged faster when the prime and the target were phonologically related, indicating that phonological information plays an important role in the processing of number words. In general, number words were processed much like other words, especially native Tibetan number words. Models of reading (e.g., Coltheart et al., 2001) commonly assume that a transformation from orthography to phonology exists during word recognition. The current finding supports the results reported by other studies of number-word processing (Campbell et al., 1999; Damian, 2004; Fias, 2001; McNeil & Warrington, 1994) in which a phonological pathway, or verbal code pathway, is proposed to be activated when processing numbers. However, previous studies made this suggestion using indirect evidence: number words were named faster than Arabic digits in a naming task (Campbell et al., 1999; Damian, 2004; Fias, 2001; Ito & Hatta, 2004). In contrast, our data provide direct evidence for the existence of this verbal pathway in number-word processing.

One might wonder why phonological information is also encoded in Chinese number words. Indeed, linguistic scientists have proposed three models of word meaning access: The Direct Access theory, the Phonological Mediation theory, and the Dual Route theory (Leck et al., 1995; Luo, 1996; Rayner et al., 1998; Rubenstein et al., 1971; Taft & van Graan 1998). The debate between these theories focuses on how we access the semantic information in visual word recognition. According to the previous findings, the role of phonology in the processing of ideographic words such as Chinese words is limited, and the semantic access of Chinese words is mainly achieved directly through the orthography. For example, Zhou et al. (1999) showed that the target word "卫生" ([wèishēng], meaning health) cannot be primed by "捷径"([jiéjìng], meaning shortcut, a homophone for "洁净," which means clean), indicating that there was no phonological mediation priming effect in Chinese word recognition. In the current study, we found a phonological effect when processing Chinese number words. One reason could be that as Tibetan was the native language, to a certain extent, it could influence the processing of Chinese number words. Participants might have been more inclined to use their native internal alphabetic writing system to process the second language (i.e., Chinese). However, a more likely reason is that phonological information is activated in Chinese reading. The follow-up studies by Zhou found that access to semantics in reading Chinese is constrained by both phonology and orthography (Zhou & Marslen-Wilson, 1999). In another study by Zhou, they even concluded that semantic information is activated at least as early and as strongly as phonological information in reading Chinese (Zhou & Marslen-Wilson, 2000). Moreover, phonological activation during Chinese character identification has been proved by other previous studies (Perfetti & Tan, 1998; Tan & Perfetti, 1999). We are more inclined to believe that phonology is inherently activated in Chinese number words recognition.

A consistent phonological priming effect was found for Arabic digit processing. The current finding indicates that phonological information is automatically encoded when people perform parity judgment tasks. However, previous studies of number processing proposed that Arabic digits do not specify the phonological codes to which they correspond and that Arabic digit processing is similar to the process of object recognition (Damian, 2004). This view is supported by several studies that suggest Arabic digits and number words are processed in different pathways (Dehaene & Cohen, 1995; Fias, 2001). However, this is clearly not the case. We believe the priming paradigm used in the present study was most likely responsible for this result. In our experiment, phonological relationships were manipulated directly to investigate whether phonology plays a role in number processing. Even though our results are inconsistent with previous studies, there are also similarities. In terms of error rates in Experiment 2, we found no significant difference between the phonological priming and non-priming conditions when the Arabic digits were primed by Chinese characters, suggesting that the influence of phonological information is limited.

How are Arabic digits and number words processed differently? Using different tasks, previous studies found a faster naming speed for number words and faster semantic access for Arabic digits (Campbell et al., 1999; Damian, 2004; Fias, 2001; Ito & Hatta, 2004). Two processing routes for Arabic digits and number words were proposed based on different tasks. Although studies suggested that Arabic digits can trigger faster access to semantic information, it is difficult to rule out the possibility that phonological information might also be used in tasks that require access to semantic codes. Why do we need less time to gain access to semantic information when we view Arabic digits than when we view number words? One possibility is that the speed is related to the frequency of use; frequently using Arabic digits for math problems could make the link between processing Arabic digits and the semantic system stronger than the link for number words. Another possibility comes from a study of patients with damage to the left hemisphere of their brains, who could still use the right brain to process Arabic digits. An extra right-brain processing path might make the processing of Arabic digits faster than number words (Anderson, Damasio & Damasio, 1990). However, our results seem to be inconsistent with these results due to the phonological encoding found when processing Arabic digits. The asemantic routes between Arabic digits and their corresponding phonological information might act too slowly (Fias, 2001). In yet another explanation, Arabic digits are assumed to be processed like objects. Miozzo et al. (2015) found that semantic information and phonological information were activated in parallel during object recognition. If this is the case, it is not surprising that we found phonological encoding when processing Arabic digits.

Link the current findings to the model of number processing

How do our current findings relate to models of number processing? The Abstract-modular Model proposed by McCloskey (1992) assumes that number processing is not notation-specific; all the number forms, including number words and Arabic digits, first map onto an abstract quantity code. The phonological information is only activated if it is needed by the task. As we described above, this model is not supported by the current findings in which phonological priming influenced processing of Arabic digits despite not being necessary. The Triple-code model developed by Deheane (1992) is an alternative that posits three different codes: a visual Arabic number form that mediates digital input, output, and calculations; an analog magnitude representation for approximate calculation and numerical-size comparisons, and an auditory-verbal code system that supports spoken and written input, output, and simple calculations. These three modules can be transcoded from one to another without the mediation of an abstract code. According to the Triple-code model, in the naming task, Arabic digits can access the visual Arabic system and be transformed into verbal codes without accessing abstract magnitude codes. Number words can directly access the auditory–verbal modules, which support naming. This is why we found a faster naming speed for the number words. Recent neuroimaging evidence support aspects of this model (Poncin Van Rinsveld & Schiltz, 2020; Skagenholt et al., 2018). Each of the three codes or representations activates different regions of the brain, which are connected to each other (Poncin et al., 2020; Skagenholt et al., 2018). However, this model needs extra assumptions to explain why Arabic digits are processed faster in categorizing tasks or other tasks that demand semantic activation. For example, one must assume that compared with number words, a stronger link exists between digits and the corresponding conceptual information. However, in the current study, although we used a parity judgment task, verbal information was activated when processing the Arabic digits. As Damian (2004) suggested, this possibility is difficult to rule out at present. On the other hand, the phonological activation that we observed in our results might have been triggered by the priming task we used. We may not be able to rule out the possibility that there could be an alternative route for semantic processing without phonological processing in advance.

Number processing issues in Tibetan-Chinese bilinguals

One issue we would like to address is the high error rates in the Tibetan condition in Experiment 1. As Fig. 3 and Table 4 showed, the error rates of the Tibetan condition were higher than the Chinese condition whether in the priming condition or non-priming condition. That is, Tibetan-Chinese participants tend to make more mistakes when they make a parity judgment of Tibetan number words, which seems unreasonable since they are native Tibetan speakers. By reading the literatures on the current situation of mathematics teaching in Tibetan areas and communicating with the participants' teachers, we think there are two possible reasons. First, from primary school, except for Tibetan lessons, the textbooks such as mathematics they used are Chinese versions. Although teachers will explain in Tibetan sometimes so that students can better understand the content of the courses, the mathematical language is Chinese (Li & Fan, 2014). Second, from middle school or high school, some Tibetan students come to the eastern provinces to study and live in a Chinese-speaking environment. Mathematics teaching in Chinese makes Chinese number words become the most frequently heard numbers. There are very few situations in which Tibetan number words are being used and heard, let alone mathematical judgment tasks such as parity judgment.

The participants in this study were native in Tibetan, and Chinese was their second language. However, Chinese as a second language did not appear to be an issue in the current study. The mathematical language they used is Chinese since they started learning math. In particular, we found a lower error rate in Chinese condition, which is consistent with the proposition by Bernardo (2001). That is, the stronger verbal code is not always in the bilingual's first language, instead, it is the language used for learning and practicing arithmetic tasks. Furthermore, the size of the error rates when participants make parity judgments of Chinese number words in the study was consistent with previous studies (Wang et al., 2007; Yang et al., 2014).

Although our participants were proficient bilinguals, another interesting finding was that number processing depending on language proficiency when we divided them into two groups. The current study showed an interaction between priming type and language proficiency. Specifically, in Experiment 1, the phonological priming effect was significantly greater for participants with low Chinese language proficiency than for those with high language proficiency, indicating that priming helps people more if they are less fluent in a language. Although we did not find that reaction time was affected by an interaction between priming type and language proficiency, we did find that error rates were affected by such an interaction. Although phonology had no effect on parity judgment error rates for participants with high language proficiency, it did have an effect on those with low language proficiency. Thus, activation of phonological information during number processing can be beneficial when language fluency is low. More specifically, Zhou et al. (1999) hypothesized that access to semantics in reading Chinese is constrained by both phonology and orthography operating in interaction with each other. The difference between high- and low-proficiency bilinguals was that low-proficiency bilinguals were slower or made more errors in the non-priming condition. For proficient bilinguals, they can quickly access the semantics of the target word through orthography and phonology in the non-priming condition. But for the unskilled bilinguals, if there is no pre-activation of the phonology by the primes, participants will spend more time completing the semantic access of the target word through the interaction of the orthography and phonology in the non-priming condition.

Conclusion

In summary, using a priming paradigm, we found consistent results across two experiments indicating that phonology is involved in the processing of numbers, regardless of whether they are written as words or digits. Semantic access provided by number words was facilitated more by phonological information if the words were Tibetan than if they were Chinese. For Arabic digits, phonological information was activated when accessing the semantics. In addition, language proficiency affected the degree to which phonologic activation improved number processing; those with low proficiency relied more on phonological encoding than those with high proficiency.

Author contributions All authors contributed to the study design. Han performed the data analysis and drafted the manuscript. Testing and data collection were performed by Wang. Cui and Zhou provided critical revisions. All authors approved the final version of the manuscript for submission.

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Declarations

Conflicts of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the Institutional Review Board of the State Key Laboratory of Cognitive Neuroscience and Learning at Beijing Normal University and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication Participants consented to publication.

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Open practices statement None of the experiments was preregistered. The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request, and they will be provided online for public access once the paper is accepted.