The Quarterly Journal of Experimental Psychology

ISSN: 1747-0218 (Print) 1747-0226 (Online) Journal homepage: http://www.tandfonline.com/loi/pqje20

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Publisher: Taylor & Francis & The Experimental Psychology Society
Journal: *The Quarterly Journal of Experimental Psychology*
DOI: 10.1080/17470218.2017.1340968

Article title:

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Running Head:

Structural Priming, Arithmetic Equation

Journal name:

Quarterly Journal of Experimental Psychology

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Structural priming from arithmetic to language in Chinese: Evidence from adults and children

Abstract

This paper explores structural integration between arithmetic and language by investigating whether the structure of an arithmetic equation influences the way children and adults interpret Chinese sentences in the form of $NP_1+VP_1+NP_2+VP_2$, where the VP_2 can attach high as a predicate of NP_1 or attach low as a predicate of NP_2. Participants first solved an arithmetic problem where the last number was to be attached high (e.g., (5+1+2)x3) or low (e.g., 5+(1+2x3)) and then provided a completion to a preamble in the form of $NP_1+VP_1+NP_2+HEN$ 'very' …, or decided on the meaning of an ambiguous sentence. The way the ambiguous sentences were completed and interpreted was primed by the structure of the preceding arithmetic problem (i.e. a high-attachment prime led to more high-attachment completions and interpretation) in both children and adults. This study found cross-domain priming from arithmetic equations to language, which offered empirical evidence for the Shared Syntactic Integration Resource Hypothesis (Patel, 2003) and the Syntactic Working Memory Theory (Kljajevic, 2010). It was also found that children were more susceptible to such priming, which provided some tentative evidence for the Incremental Procedural Account proposed by Scheepers et al. (2011).

Key words: structural priming, arithmetic equations, Chinese sentences

INTRODUCTION

Cognition is often held to consist of a set of distinct modules, each specialized to a specific domain and processing mode. For example, the way people process language is intuitively different from the way they do arithmetic or music. However, a range of studies have demonstrated a potential link between linguistic cognition and other cognitive domains, involving shared structural processing between linguistic and musical cognition (Koelsch, Gunter, Witfoth, & Sammler, 2005; Slevc, Rosenberg, & Patel, 2009; Van de Cavey, & Hartsuiker, 2016); linguistic and mathematical cognition (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999); as well as linguistic and sequential processing (Lelekov, Franck, Dominey, & Georgieff, 2000). This suggests that there might be shared structural representations between language and other cognitive domains.

There are several accounts of shared structural integration across different cognitive domains. Patel (2003) proposed the Shared Syntactic Integration Resource Hypothesis (SSIRH), which claims that while structure sequences in, for instance, music and language, may engage domain-specific knowledge networks, they also require common processing abilities to execute the knowledge for structural integration. So it is highly plausible that the rules on which this integration is based are domain-specific, but the resources that support this integration might not be domain specific. In other words, structural sequences in music and language may be organized on the basis of domain-general structural integration mechanisms. The Syntactic Working Memory Theory (SWM) (Kljajevic, 2010) analyzes the shared representation of structures from the perspective of syntactic working memory resources, claiming that constructing a partial structural representation through the integration of available structural information might critically depend on domain-general syntactic working memory resources.

To investigate shared structural integration in language as well as its relation with other cognitive domains, recent research has employed the structural priming paradigm (Scheepers, 2003; Scheepers et al. 2011; Scheepers & Sturt, 2014). Structural priming is a methodology based on the phenomenon that people respond preferentially to stimuli (e.g. sentences) structured in the same way as previous stimuli have been (Pickering & Ferreira, 2008). In language domains, previous priming studies have focused on syntactic structures including datives (Bock, 1986; Bock & Griffin, 2000; Loebell & Bock, 2003; Wang, 2009; Cai et al., 2015), active and passive sentences (Bock & Loebell, 1990; Savage, Lieven, Theakston, & Tomasello, 2003; Lei & Wang, 2009), and sentences with transitive or intransitive verbs (Van Gompel, Arai, & Pearson, 2012; Zhao, 2014). In addition, some studies have indicated that different aspects of linguistic input might be primed in the subsequent language processing, including the linear order and the grammatical functions of sentences' constituents (Chang, Bock, & Goldberg, 2003; Cai, Pickering, & Branigan, 2012; Cai et al., 2015). Instead of adopting syntactic structures as primes, Scheepers et al. (2011) initially employed mathematical equations as primes, and they confirmed the existence of a cross-domain structural priming effect from the arithmetic equations to the production of English relative sentences.

Scheepers et al. (2011) further proposed two different accounts of structural priming between structural equations and relative clause attachment. One is the 'Representational Account', assuming that people retain global structural representations of equations and sentences in working memory. The other is the 'Incremental Procedural Account', which suggests that what is really primed during arithmetic and language processing is the combinatorial choice. To be specific, equations and sentences are generally processed from left to right; however, once they encounter a combinatorial choice (a relative pronoun, a multiplication or division operator), the sequence of processing induces a revision whereby the critical final element (the relative pronoun, multiplication or division operator) is integrated into the previously built structure, either by combining with a more complex expression on its left (high attachment) or with a less complex expression on its left (low attachment). The relative pronoun needs to be combined with a previous expression that has already been incorporated into the partial tree representation. For example, a sentence fragment ‘The tourist guide mentioned the bells of the church that…’, the relative pronoun *that* will trigger structural revision. If *that* combines with the simpler phrase *the church*, it will be a low-attachment interpretation. While if it combines with the more complex phrase *the bells of the church*, it will be a high-attachment interpretation. Recently, Scheepers & Sturt (2014) confirmed that structural priming effects also hold in the reverse direction, i.e., from linguistic to mathematical processing. They established that cross-domain structural priming is bi-directional, supporting the idea that shared structural representations are equally accessible from language to mathematics.

This study aims to provide further evidence for the existence of a domain-general structuring system, upholding the notion of the Syntactic Working Memory Theory (SWM) (Kljajevic, 2010) that is shared across domains, and the idea of the Shared Syntactic Integration Resource Hypothesis (SSIRH) (Patel, 2003, 2008) which assumes domain-general representational systems. A statement of direct priming from arithmetic to language, which could be interpreted as priming of structural dependencies, would strongly suggest that the priming can persist across domains. Such persistence would further indicate that the arithmetic and linguistic domains may overlap in an important aspect of structural integration. Domain-general resources, such as the rapid working memory resources, may be involved in this priming process.

The current study extends the research of Scheepers et al. (2011) and Scheepers & Sturt (2014) in several ways. First, most previous related studies have focused on inflectional languages such as English and German, while the current study focuses on Mandarin Chinese, in order to provide more cross-linguistic evidence on the possible universality of priming effects from abstract structures to language. Second, while previous studies typically used language completion to investigate structural influences from non-language domains (Scheepers et al., 2011), the current study attempted to test whether cross-domain structural priming generalizes across task modalities and whether tasks differentially affect the occurrence or degree of priming effects by comparing the two task modalities.

Last but not least, if a domain-general structure system does exist, then the issue whether there is a developmental trajectory for this system still needs to be explored. As an automatic and implicit process (Pickering & Branigan, 1999; Chang, 2002; Chang et al., 2006; Chang, Dell, Bock, & Griffin, 2000), structural priming can be hypothesized to be more prominent in young children. Therefore, in the current study, we selected two age groups to explore the differences between adults and children in processing structures.

The current study adopted a sentence completion task and an ambiguous sentence judgment task to study cross-domain structural priming in both adults and children. It addresses the following research questions:

1) Is there structural priming from arithmetic equations to sentence production and comprehension in Chinese?

2) Do children and adults show similar or different structural priming effects in the two tasks?

3) Do arithmetic and language share similar structural representations?

CHINESE STRUCTURE *NP_1+YOU+NP_2+HEN+AP* and SIMPLE ARITHMETIC EQUATIONS

Most studies of structural priming are from sentences to sentences, either within one language or across languages. In the current paper, we selected the ambiguous Chinese sequence *NP_1+YOU+NP_2+HEN+AP* as the experimental structure. Here *AP* can be attached to *NP_1* or *NP_2* or both in different conditions, which is similar to the relative sentence in English. For example, the Chinese sentence (1) *Laowang you ge nver hen jiaoao* has two possible structural analyses (hence two possible meanings) (Shao, 1991). The *AP* phrase *jiaoao* 'proud' can be attached high to *Laowang* and such a high attachment analysis results in the interpretation of *Laowang* being proud (i.e. 1a); alternatively, the *AP* can be attached low to the *NP nver*, resulting in the interpretation of 'the daughter being proud' (i.e. 1b). In Chinese, *HEN* 'very' is an adverb and usually modifies an adjective, and in some occasions *HEN+AP* can be the predicate of a sentence. In this case, NP_1+*YOU*+NP_2 is deemed as an integral event, corresponding to a clause in English. Then, *AP* modifies the whole event but not any of the individual nouns, which we call a comment-like sentence. Therefore as shown in Figure 2, we regard *HEN*+*jiaoao* as *VP*. When sentence (1) is interpreted as (1b) and the *AP* could only modify NP_2, it is a low-attachment structure and the main clause of this sentence is *Laowang you ge nver* 'Mr. Wang has a daughter', therefore, it is natural to regard *YOU* as the head of *VP*.

(1) *Laowang you ge nver hen jiaoao.*

Mr. Wang has a daughter very proud.

1a. Mr. Wang is very proud because he has a daughter.

1b. Mr. Wang has a daughter who is very proud.

Zhao and Shao (2007) further showed that the ambiguity of (1) is related to animacy. Since NP_1 phrase *Laowan*g is animate and *qich*e 'car' is inaminate, while *AP* phrase *jiaoao* is normally used to modify animate subjects, here *jiaoao* can only refer to *Laowang* in this sentence and (2b) is not acceptable. Thus animacy of *NP* is one of the key factors in determining how the *AP* is to be attached.

(2) *Laowang you liang qiche hen jiaoao.*

Mr. Wang has a car very proud.

2a. Mr. Wang is very proud because he has a car.

*2b. Mr. Wang has a car which is very proud.

Analagously, simple arithmetic equations can form hierarchical structures by operation symbols, similar to the Chinese structure NP_1+*YOU*+NP_2+*HEN*+*AP*. Equation (3a), for instance, is a high-attachment structure (where 3 is multiplied with the sum of the first three digits) while (3b) is a low-attachment structure (where

3 is multiplied with the preceding number 2).

(3) a. (5+1+2)x3

b. 5+(1+2x3)

According to the operation rules, the high-attachment equation (Figure 1, left) is ordered from left to right, similar to the high-attachment sentence (Figure 2, left); the low-attachment equation (Figure 1, right) is ordered from right to left, similar to the low-attachment sentence (Figure 2, right).

--- Insert Figure 1 about here ---

--- Insert Figure 2 about here ---

METHOD

Participants. 27 adults and 27 children were recruited, all of whom were native speakers of Mandarin. Adults were college students between the ages of 18 and 19 (Mean age=18.3, *SD*=.602), recruited from Hunan University. The children came from Hunan University Affiliated Primary School and their ages were between 10 and 11 (Mean age=10.5, *SD*=.52). They had all grasped simple arithmetic equation rules.

Materials. Experimental materials were composed of two parts: materials for the sentence completion task and materials for the sentence comprehension task. There were 24 sets of materials and 26 structurally unrelated fillers (including 13 sentence fragments and 13 equations, which cannot be classified as high attachment or low attachment structures). The materials were compiled into a questionnaire in a Latin-square fashion and were presented in a quasi-random order such that each prime-target pair was separated by one intervening filler item. In total, the researchers designed 9 different groups of questionnaires, each group had 3 copies; therefore there were 27 paper questionnaires (9x3).

Materials for the sentence completion task. The sentence completion task used 24 sets of materials. Each set consisted of one of the three arithmetic primes (4a, 4b or 4c) and a sentence fragment that was to be completed (5a).The arithmetic primes were arithmetic problems to be solved by participants. To make sure that they were all easily solvable by both child and adult participants, these problems always used single-digit integers and the results were positive integers. Both the high- and low-attachment primes were composed of four numbers and three operators. Brackets (parentheses) were used in such a way that, to correctly solve a problem, participants needed to multiply the last number with the sum of the first three digits for the high-attachment problem (e.g., 4a) or to multiply the last number with the preceding number in the low-attachment problem (e.g., 4b). Since the bracketing structure was a helpful visual cue for strengthening the priming effect in mathematically less adept participants (Scheepers et al., 2011), the researchers expected this to enhance the priming effect. The baseline equations, composed of only two numbers and an arithmetic operator, were neutral in terms of the hierarchical structures in question. The target sentence fragment to be completed used the format of NP_1+*YOU*+NP_2+*HEN*____ (e.g., 5a). The adverb *HEN* 'very' implied that the sentence should be complemented by an adjective. To reduce ambiguous responses, the researchers restricted NP_1 (*Xiaoli*) to be animate, and NP_2 (*zuanjie* 'diamond ring') to be inanimate such that it was easy to discern whether a completion following *HEN* should be attached to the first *NP Xiaoli* (e.g., if the response is *kaixin* 'happy') or the second *NP zuanjie* (diamond) (e.g., if the response is *shanyao* 'shiny'). To avoid the participants guessing the research question, 26 structurally unrelated fillers including 13sentence fragments and 13 equations were randomly inserted. At the beginning of each questionnaire, 3 fillers were presented, and one sentence or equation filler was inserted before each prime-target pair. Three groups of paper questionnaires were created in a Latin-square manner such that each item only occurred once and always in different prime conditions. Each questionnaire contained 24 target items and 26 filler items, whose order was individually randomized.

(4a) High-attachment arithmetic prime: $(2+2+1)\times7 =$

(4b) Low-attachment arithmetic prime: $4+(6+1\times7) =$

(4c) Baseline arithmetic prime: $8+4=$

(5a) *Xiaoli you ke zuanjie hen*_________.

Xiaoli have a diamond very

(5b) *Xiaoli you ke zuanjie hen kaixin*.

Xiaoli have a diamond very happy

(Xiaoli is very happy because she has a diamond).

(5c) *Xiaoli you ke zuanjie hen shanyao*.

Xiaoli have a diamond very shiny

(Xiaoli has a diamond that is very shiny).

Materials for the ambiguous sentence judgment task. The ambiguous sentence judgment task also had 24 sets of materials, each containing an arithmetic prime as those in (4) and an ambiguous sentence. The arithmetic prime was either a high-attachment, low-attachment or baseline prime (4a, 4b or 4c). The ambiguous sentence was in the form of NP_1+*YOU*+NP_2+*HEN*+*AP*. Since the animacy of the *NPs* is a key factor in determining how the *AP* is to be attached, the researchers always used animate *NPs* so as to induce ambiguity. Every ambiguous sentence was followed by two choices, each containing a short phrase that captured one of the two alternative meanings of the ambiguous sentence as in (6). Like the sentence completion task, there were 26 structurally unrelated fillers inserted randomly between prime-targets in the ambiguous sentence judgment task. Also, three groups of paper questionnaires were created, with the items in each group randomly arranged for each participant.

(6) *Laowang you ge nver hen* *<u>jiaoao</u>*.

Mr. Wang has a daughter very proud.

A. *Laowang hen jiaoao.* B. *Nver hen jiaoao.*

Mr. Wang very proud Daughter very proud

Procedures. Participants were tested individually. They completed two pencil-and-paper questionnaires (sentence completion and sentence judgement). In both tasks, participants answered an arithmetic question in writing and then completed a sentence completion (proving phrases to complete the sentence) or judgment task (making a choice). Specifically, arithmetic primes were firstly presented for participants to complete by writing their answers down on questionnaire papers. Then in the sentence completion task, target sentence fragments were provided for subjects to complete. During the sentence judgment task, subjects were required to make choices between choice A or B as in (6). If subjects understood the sentence to be (6A), it was high-attachment and choice A would be made. If the participant understood the sentence to be (6B), it was low-attachment and choice B would be made. Subjects were required to complete the questionnaire in the given order and revision on previously completed items was not allowed. All the participants were required to finish a questionnaire in 25 minutes, 15 minutes for the sentence completion task and 10 minutes for the sentence judgment task.

Scoring. Responses were excluded from further scoring for trials where participants failed to give the correct answers to the arithmetic problems. In the sentence completion task, a completion was coded as a high-attachment response if the given completion (together with *HEN* 'very') clearly modified NP_1 and as a low-attachment response if the given completion clearly modified NP_2. Responses where the completion was ambiguous in terms of which *NP* it modified (e.g., *Xiaoming you ge shouji hen ku* 'Xiaoming has a cellphone, very cool', where *ku* 'cool' could refer to either 'Xiaoming' or the 'cellphone') or responses that did not make sense were coded as other responses and were excluded from the main analyses. Responses in the ambiguous sentence judgment task were coded as high-attachment or low-attachment responses depending on the phrase that participants indicated as capturing the meaning in the sentence.

RESULTS

Three types of statistical analysis were conducted. First, Friedman Tests were performed for the omnibus analyses across the three priming conditions (baseline, low-attachment, high-attachment). Then 2-tailed Wilcoxon Signed-Ranks tests were conducted for pairwise comparisons between (a) the baseline and low-attachment priming conditions, (b) the baseline and high-attachment priming conditions and (c) the low-attachment and high-attachment priming conditions. Finally, two-way repeated-measures ANOVA were conducted to compare children's data with adults' in each task. Results are presented in the following by each task.

Sentence completion by adults. Participants correctly solved the arithmetic problems 98% of the time. Overall, there were 73% low-attachment, 21% high-attachment, and 6% unclassifiable target-responses. Compared with baseline priming conditions (0.79), adults tended to produce more low-attachment completions in low-attachment priming conditions (0.82) but fewer low-attachment completions in high-attachment priming conditions (0.71). The Friedman test revealed a significant difference of low-attachment target completions across the three priming conditions by participants ($\chi^2(2)=10.02$, $p<.01$) and by items ($\chi^2(2)=10.57$, $p<.01$). The results of the 2-tailed Wilcoxon Signed-Ranks tests indicated that the difference between high-and low-attachment priming was significant by both participants ($p<.01$) and items ($p<.01$); the difference between low-attachment priming and baseline was significant by items ($p<.05$) and the difference between baseline and high-attachment was significant by participants ($p<.05$). No other effects achieved significance by either participants or items. The significant difference between high- and low-attachment priming conditions by both participants and items indicated a structural priming effect from arithmetic equations to the Chinese structure $NP_1+YOU+NP_2+HEN+AP$ in the sentence completion task by adults. Notably, the baseline was only significantly different from the high primes by participants and significantly different from the low primes by items, indicating that the priming effect under the baseline condition might be slightly indistinguishable from low and high primes. This could be attributed to the fact that though there was a priming effect, such effect was not large enough for adults in this task.

--- Insert Figure 3a about here ---

Ambiguous sentence judgment by adults. Participants correctly solved 97% of all the arithmetic problems. For the sentence judgement task, there were 32% low-attachment, 68% high-attachment target-responses. Figure 3b illustrates the proportion of low-attachment choices in the three priming conditions. The Friedman test revealed a significant difference of low-attachment target completions across the three priming conditions by participants ($\chi^2(2)=17.63$, $p<.001$) and by items ($\chi^2(2)=8.97$, $p<.02$). The results of the 2-tailed Wilcoxon Signed-Ranks tests indicated that the difference between high- and low-attachment priming was significant by both participants ($p<.01$) and items ($p<.01$); the difference between low-attachment priming and baseline was not significant either by participants or items; the difference between baseline and high-attachment was significant by both participants ($p<.05$) and items ($p<.01$). The significant difference between high- and low-attachment priming conditions by both participants and items indicated a structural priming effect from arithmetic equations to the Chinese structure $NP_1+YOU+NP_2+HEN+AP$ in the sentence completion task by adults. Notably, adults tended to make more low-attachment choices in baseline priming conditions than in low or high priming conditions. The difference was significant between baseline and high-attachment priming conditions, but not significant between baseline and low-attachment priming conditions, indicating that the baseline condition was hardly distinguishable from low primes. Combined with the results of the former sentence completion task, it is plausible that the priming effect from arithmetic to language might not be very strong for adults.

--- Insert Figure 3b about here ---

Sentence completion by children. Children correctly solved the arithmetic problems 95% of the time. Overall, there were 63% low-attachment, 29%

high-attachment, and 8% unclassifiable target-responses. Compared with baseline priming conditions (0.68), children tended to produce more low-attachment completions in low-attachment priming conditions (0.79) but fewer low-attachment completions in high-attachment priming conditions (0.61). The Friedman test revealed a significant difference of low-attachment target completions across the three priming conditions by participants ($\chi^2(2)=17.08$, $p<.001$) and by items ($\chi^2(2)=6.04$, $p<.05$). Then, results of 2-tailed Wilcoxon Signed-Ranks tests indicated that the difference between high-and low-attachment priming was significant by both participants ($p<.01$) and items ($p<.05$); the difference between low-attachment priming and baseline was significant by both participants ($p<.01$) and items ($p<.05$); the difference between baseline and high-attachment was not significant either by participants or items. Differently from the previous two tasks with adults, the low-attachment priming condition in this task was significantly higher than both baseline and high-attachment priming condition, indicating a seemingly larger structural priming effect from arithmetic equations to the Chinese structure NP_1+*YOU*+NP_2+*HEN*+*AP* by children. Thus, a two-way repeated-measures ANOVA test was conducted to compare the child and adult data. Since the baseline condition was slightly indistinguishable from low and high primes by adults, to reduce the complexity of the analysis, a straightforward 2 (within-subjects factor, Prime Conditions: low vs. high) x 2 (between-subjects factor, Age Groups: children vs. adults) analysis was adopted. Results showed that there was an interaction between age groups and prime conditions, $F(1,52)=6.71$, $p<.05$, and the main effect of prime conditions and age groups were both significant, $F_1(1,52)=23.85$, $p<.001$;$F_2(1,52)=5.10$, $p<.05$, which indicated that children and adults indeed manifested different magnitudes of priming effects.

--- Insert Figure 4a about here ---

Ambiguous sentence judgment by children. Participants correctly solved 94% of all the arithmetic problems. Overall, there were 41% low-attachment, 59%

high-attachment target-responses. Figure 4b illustrates the proportion of low-attachment choices in the three priming conditions. Compared with baseline priming conditions (0.47), children tended to choose more low-attachment options in low-attachment priming conditions (0.52), but less low-attachment options in high-attachment priming conditions (0.24). The Friedman test revealed a significant difference of low-attachment target completions across the three priming conditions by participants ($\chi^2(2)=28.42$, $p<.001$) and by items ($\chi^2(2)=12.97$, $p<.002$). The results of the 2-tailed Wilcoxon Signed-Ranks tests indicated that the difference between high-and low-attachment priming was significant by both participants ($p<.001$) and items ($p<.01$); the difference between low-attachment priming and baseline was not significant either by participants or items; the difference between baseline and high-attachment was significant by both participants ($p<.001$) and items ($p<.05$). The significant difference between high- and low-attachment priming conditions indicated a structural priming effect from arithmetic equations to the Chinese structure NP_1+*YOU*+NP_2+*HEN*+*AP* in sentence judgment by children. Compared with adults' performance, children made more low-attachment choices in low-attachment prime conditions than in the other two prime conditions, suggesting that children might be more susceptible than adults to priming. Thus, a 2 (primes: low vs. high) x 2 (ages: children vs. adult) repeated-measures ANOVA test was conducted. Results showed that, in the sentence judgment task, there was also an interaction between age groups and prime conditions $F(1,52)=7.28$, $p<.05$, and the main effect of prime conditions and age groups were both significant, $F_1(1,52)=56.47$, $p<.001$; $F_2(1,52)=8.76$, $p<.05$, which indicated that children and adults indeed manifested different priming effects.

--- Insert Figure 4b about here ---

DISCUSSION

The present study demonstrated abstract structural priming effects from arithmetic equations to the Chinese structure NP_1+YOU+NP_2+HEN+AP in both tasks. Children generally showed a higher degree of structural priming effects than adults in equivalent conditions.

By demonstrating direct priming from attachment choices in arithmetic equations to language, the present study provided some evidence for a domain-general structuring system and shared structural processing. These results are consistent with the notion of the Syntactic Working Memory Theory (SWM) (Kljajevic, 2010) and support models such as the Shared Syntactic Integration Resource Hypothesis (SSIRH) (Patel, 2003, 2008), indicating that the arithmetic and linguistic domains overlap in some aspects of structural integration and that the resources underlying 'structural integration mechanisms' in mathematics and language processing are domain-general to some extent.

In the present study, there was an interaction between age groups and prime conditions in the sentence completion task, $F(1,52)=6.71$, $p<.05$, as well as in the sentence judgment task, $F(1,52)=7.28$, $p<.05$, thus children and adults indeed displayed different priming effects. Moreover, differently from the indistinguishable priming effects under the baseline priming condition for adults, children were primed across all three priming conditions in both tasks, indicating that children might be more susceptible to priming. The stronger priming effects in children might be ascribed to the differences in computational process between children and adults. For instance, children usually spend a longer time calculating equations and comprehending sentences than adults, therefore, it took a longer time for children to complete the two tasks, which might account for the stronger priming effects on children than in adults. Moreover, from the perspective of calculation strategies, adult participants might apply learned methods to simplify the computational process and might not follow the normal calculation order, which might have weakened the priming effects. Compared with adults, young children are less practiced in language use and have fewer computational resources available and hence are more susceptible to priming effects.

The relatively stronger priming effects on children may also shed light on the mechanisms underlying the attachment priming effects. Scheepers et al (2011) proposed that attachment priming effects result either from the global structural representations of equations and sentences (Representational Account), or an activation of the combinational nodes and hierarchical syntactic configuration (Incremental Procedural Account). As we have mentioned, the stronger priming effects on children might be a consequence of different computational process between adults and children. Schneider et al. (2012) have found that adults and children do have different computational order. Mathematically highly adept adult participants do not necessarily process arithmetic equations in a strictly left-to-right fashion while children who are mathematically less adept might have a stronger tendency to process equations strictly incrementally, from left to right. Therefore, the fact that priming was stronger for children than for adults in the present study might (at least tentatively) be taken as evidence in support of the 'Incremental Procedural Account' (Scheepers et al., 2011), according to which priming from mathematics to language relies on left-to-right processing of both equations and sentences. This hypothesis needs to be further tested by appropriate on-line measures (e.g., eye-tracking).

The current study also yielded the interesting result that the attachment priming effect could be achieved across different syntactic domains. In Scheepers et al.'s (2011) research of English relative clauses, high (NP_1)- vs. low (NP_2)-attachments were both within the domain of the complex object noun-phrase (e.g., NP_1 a friend of [NP_2 a colleague]). This showed that priming effects could be observed for high- and low- attachments within the same syntactic domains. By contrast, in our Chinese structure NP_1+*YOU*+NP_2+*HEN*+*AP*, the high versus low attachment options here involved attachments to different syntactic domains, to the Sentence (S)-node in the high-attachment case, (e.g., [*S* [*S'*[NP_1 *YOU* NP_2]] *HEN AP*]]]), and to the Object *NP*-node in the low attachment case, (e.g., [*S* NP_1 [*VP* NP_2[*HEN AP*]]]). Such results could provide strong evidence for the strength of priming effects at different syntactic nodes within language structures. Regarding the question to what extent arithmetic structures are required to be isomorphic to linguistic structures to trigger the priming effects, further research is called for.

Finally, for the structure NP_1+YOU+NP_2+HEN+AP, both adults and children showed a clear preference for low-attachment in the sentence completion task. Conversely, the two groups showed a clear preference for high-attachment in the ambiguous sentence judgment task. These distinctions might be attributed to the specific properties of these two tasks. In the sentence completion task, a sentence fragment NP_1+YOU+NP_2+HEN____was given, in which all NP_1 were animate and all NP_2 were inanimate. When participants completed sentences, they tended to produce low-attachment structures. The results aligned with the Dependency Locality Theory (Gibson, 2000), which assumes that structures will be maintained in memory and it will be more difficult for two elements to be integrated when there is a larger distance between them. According to this theory, the distance between *AP* and NP_2 was shorter than that between *AP* and NP_1, thus *AP* was more attached to NP_2 than NP_1 and the cost of integrating *AP* and NP_2 would be less. Further, memory restrictions could have led participants to pay more attention in the sentence completion task to the blank part of the fragment which was placed at the end of the sentence, attaching *AP* to NP_2; whereas in the judgment task, completed sentences and two options had already been provided for subjects to choose. In Mandarin Chinese, completed sentences were usually interpreted in the form of topic-comment structures, thus it was more natural for participants to treat NP_1+YOU+NP_2 as the topic (namely, an integral event, corresponding to a clause in English), deem *YOU 'have'*+NP_2 (*you ge nver*) 'has a daughter' as a kind of parenthesis, while treating *HEN*+*AP* as a comment, which described the whole event. Therefore, participants showed a clear preference for high-attachment in the ambiguous sentence judgment task.

The authors do acknowledge some shortcomings in the design of this study. Firstly, the selected Chinese specific structure was slightly flexible, so participants sometimes produced unclassifiable structures, such as ambiguous sentences and topic constructions. Secondly, the study design did not fully counterbalance the order of administration of the completion and judgment tasks, so it is possible that there might be an effect of fatigue on performance in the later task. However, the authors compared the participants' arithmetic performance between the two tasks and found no difference in accuracy, so at least in the present study, they consider that the lack of counterbalancing for the two tasks does not undermine the validity and reliability of the data. All unclassifiable structures were also removed from the analysis, which might lessen the structure priming effects. Finally, the numbers of participants and prime-target pairs in this research were relatively small.

Nevertheless, there are clear findings which bear on current theories of shared structural representation. In summary, there were priming effects from arithmetic equations to the Chinese structure $NP_1+YOU+NP_2+HEN+AP$. The existence of these effects confirms that arithmetic and language share similar structural representations and offers some empirical evidence for the Shared Syntactic Integration Resource Hypothesis (SSIRH) (Patel, 2003) and the Syntactic Working Memory Theory (SWM) (Kljajevic, 2010) accounts.

CONCLUSION

The present paper investigated the structural priming from arithmetic equations to the specific Chinese syntactic structure $NP_1+YOU+NP_2+HEN+AP$. The above results showed that: 1) there were structural priming effects from arithmetic equations to Chinese specific structure $NP_1+YOU+NP_2+HEN+AP$; 2) a larger structural priming effect was shown on children than on adults in the two tasks; 3) arithmetic and language can be assumed to share similar structural representations.

SUPPLEMENTAL MATERIAL

The Supplemental Material for this paper can be found at the address (online address to be filled in)

REFERENCES

Bock, J. K. (1986).Syntactic persistence in language production. *Cognitive Psychology*, 18, 355-387.

Bock, J. K., & Griffin, Z. M. (2000). The persistence of structural priming: Transient activation or implicit learning? *Journal of Experimental Psychology*, 129 (2), 177-192.

Bock, J. K., & Loebell, H. (1990).Framing sentences. *Cognition*, 35, 1-39.

Cai, Z. G., Pickering, M. J., Wang, R., & Branigan, H. P. (2015). It is there whether you hear it or not: Syntactic representation of missing arguments. *Cognition*, 136, 255-267.

Chang, F. (2002). Symbolically speaking: A connectionist model of sentence production. *Cognitive Science: A Multidisciplinary Journal*, 26(5), 609-651.

Chang,F., Dell, G., & Bock, K. (2006).Becomingsyntactic.*PsychologicalReview*,113(2), 234-272.

Chang, F., Dell, G. S., Bock, J. K., & Griffin, Z. M. (2000). Structural priming as implicit learning: A comparison of models of sentence production. *Journal of Psycholinguistic Research*, 29, 217-229.

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. *Science*, 284, 970-974.

Frazier, L. (1979). *On comprehending sentence: Syntactic parsing strategies*. Unpublished doctoral dissertation, University of Conneticut.

Frazier, L., & Clifton, C. (1996).*Construal*. Cambridge, MA: MIT Press.

Kljajevic, V. (2010). Is syntactic working memory language specific? *Psihologija*, 43(1), 85–101. http://dx.doi.org/10.2298/PSI1001085K.

Lei, L. & Wang, T.S. (2009). Bilingual syntactic representation: Evidence from syntactic priming of Chinese-English. *Modern Foreign Languages,* 2, 158–166.

Lelekov, T., Franck, N., Dominey, P. F., & Georgieff, N. (2000).Cognitive sequence processing and syntactic comprehension in schizophrenia. *Neuroreport*, 11, 2145–2149.

Loebell H. & Bock J.K. (2003).Structural priming across languages. *Linguistics,* 41 (5), 791–824.

Patel, A. D. (2003). Language, music, syntax and the brain. *Nature Neuroscience*, 6, 674–681.

Pickering, M. J. & Branigan, H. P. (1998). The representation of verbs: Evidence from syntactic priming in language production. *Journal of Memory and Language*, 39 (4), 633–651.

Pickering, M. J., & Branigan, H. P. (1999).Syntactic priming in language production. *Trends in cognitive sciences*, 3(4), 136-141.

Pickering, M. J., & Ferreira, V. (2008). Structural priming: A critical review. *Psychological Bullet*, 134, 427–459.

Savage, C., Lieven, E., Theakston, A. L., & Tomasello, M. (2003).Testing the abstractness of children's linguistic representations: Lexical and structural priming of syntactic constructions in young children. *Developmental Science*, 6 (5), 557–567.

Shao, J.M. (1991). Discussion of disambiguating principles. *Language Teaching and Linguistic Studies*, 1, 39–50.

Schneider, E., Maruyama, M., Dehaene, S., & Sigman, M. (2012). Eye gaze reveals a fast, parallel extraction of the syntax of arithmetic formulas. *Cognition*, 125(3), 475-490.

Scheepers, C. (2003). Syntactic priming of relative clause attachments: Persistence of structural configuration in sentence production. *Cognition*, 89, 179–205.

Scheepers, C., Sturt, P., Martin, C. J., Myachykov, A., Teevan, K., & Viskupova, I. (2011). Structural priming across cognitive domains: From simple arithmetic to relative clause attachment. *Psychological Science*, 22, 1319–1326.

Scheepers, C., & Sturt, P. (2014). Bidirectional syntactic priming across cognitive domains: From arithmetic to language and back. *Quarterly Journal of Experimental Psychology*, 67, 1643–1654.

Van Gompel, R. P. G., Arai, M., & Pearson, J. (2012).The representation of mono- and intransitive structures. *Journal of Memory and Language*, 66, 384–406.

Van de Cavey, J. & Hartsuiker, R. J. (2016). Is there a domain-general cognitive structuring system? Evidence from structural priming across music, math, action descriptions, and language. *Cognition*, 146, 172-184.

Wang, M. (2009). Effects of language proficiency and task type on structural priming in L2 production of English dative constructions. *Modern Foreign Languages,* 3, 276–286.

Zhao, C. (2014).The category effects on L2 syntactic representation: Evidence from structure priming. *Foreign Language Teaching and Research*, 46 (2), 235–245.

Zhao, C. L., & Shao, J. M. (2007). Disambiguating principles of NP_1 You NP_2 Hen AP. *Study in Languages and Linguistics*, 27 (2), 79–83.

FIGURE CAPTIONS

Figure 1 Hierarchical Structure of Simple Arithmetic Equations

Figure 2 Hierarchical Structure of Chinese Specific Structure

Figure 3a Results from Adults' Sentence Completion Task： mean proportion of low-attachment completions under the three priming conditions. Error bars represent standard errors of the means.

Figure 3b Results from Adults' Sentence Judgment Task： mean proportion of low-attachment choices under the three priming conditions. Error bars represent standard errors of the means.

Figure 4a Results from Children's Sentence Completion Task: mean proportion of low-attachment completions under the three priming conditions. Error bars represent standard errors of the means.

Figure 4b Results from Children's Sentence Judgment Task: mean proportion of low-attachment choices under three priming conditions. Error bars represent standard errors of the means.

Appendix: Examples of Stimulus Materials

1. Sentence completion task

item1

high-attachment prime：(6+8+1)×4=

low-attachment prime：6+(8+1×4)=

baseline prime：6×14=

target structure：军人 有 个 徽章 很____________________。

Junren you ge huizhang hen____________________.

Soldier has a badge very____________________.

item 2

high-attachment prime：(3+5+4)×2=

low-attachment prime：3+(5+4×2)=

baseline prime：7+4=

target structure：妹妹 有 个 气球 很____________________。

Meimei you ge qiqiu hen____________________.

Sister has a balloon very____________________.

item 3

high-attachment prime：(7－2+6)×5=

low-attachment prime：7－(2+6×5)=

baseline prime：22－4=

target structure：哥哥 有 台 手机 很____________________。

Gege you tai shouji hen____________________.

Brother has a cellphone very____________________.

item 4

high-attachment prime：(11+5+8)÷4=

low-attachment prime：11+(5+8÷4)=

baseline prime：28－11=

target structure：小丽 有 颗 钻戒 很____________________。

Xiaoli you ke zuanjie hen____________________.

Xiaoli has a diamond ring vey____________________.

item 5

high-attachment prime：(23－5+2)×4=

low-attachment prime：23－(5+2×4)=

baseline prime：22×4=

target structure：妈妈 有 条 旗袍 很____________________。

Mama you tiao qipao hen____________________.

Mother has a cheongsam very____________________.

2. Sentence judgment task

item 1

high-attachment prime：(20－6+1)×5=

low-attachment prime：20－(6+1×5)=

baseline prime： 26－4=

target structure：老王　有 个　女儿　很　骄傲。

Laowang　you ge　never　hen　jiaoao.

Mr. Wang　has a　daughter　very　proud

A.老王　很 骄傲。　B 女儿 很　骄傲。

A. Laowang hen jiaoao.　B. Nver　hen　jiaoao.

Mr. Wang very proud　Daughter very proud

item 2

high-attachment prime：(19+5－4)÷4=

low-attachment prime：19+(5－4÷4)=

baseline prime： 24÷12=

target structure：奶奶　有　个　孙女　很　快乐。

Nainai　you　ge　sunnv　hen　kuaile.

Grandma　has　a　granddaughter　very　happy.

A.奶奶　很　快乐。　B. 孙女　很　快乐。

A. Nainai　hen　kuaile.　B. Sunnv　hen　kuaile.

Grandmm　very　happy　Granddaughter　very　happy

item 3

high-attachment prime：(4+16－3)×2=

low-attachment prime：4+(16－3×2)=

baseline prime： 11×4=

target structure：老头　有　个 网友　很　时尚。

Laotou　you　ge　wangyou　hen　shishang.

Old man　has　a　net friend　very　fashionable.

A. 老头　很　时尚。　B. 网友　很　时尚

A. Laotou　hen　shishang　B. Wangyou　hen　shishang

Old man　very　fashionable　Net fiend　very　fashionable item 4

high-attachment prime：(11－2+18)÷9=

low-attachment prime：11－(2+18÷9)=

baseline prime： 22－4=

target structure：保安 有 个 孙子 很 兴奋。

Baoan you ge sunzi hen xingfen.

Security guard has a grandson very excited.

A. 保安 很 兴奋。 B. 孙子 很 兴奋。

A. Baoan hen xingfen. B. Sunzi hen xingfen.

Security guard very excited Grandson very excited

item 5

high-attachment prime：(3+11+6)×2=

low-attachment prime：3+(11+6×2)=

baseline prime： 11+14=

target structure：少女 有 个 男友 很 害羞。

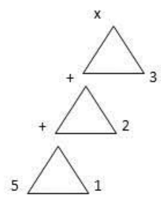
Shaonv you ge nanyou hen haixiu.

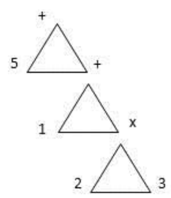
Girl has a boyfriend very shy

A.少女 很 害羞。 B. 男友 很 害羞。

A. Shaonv hen haixiu B. Nanyou hen haixiu.

Girl very shy Boyfriend very shy


x
+
3
+
2
5
1


+
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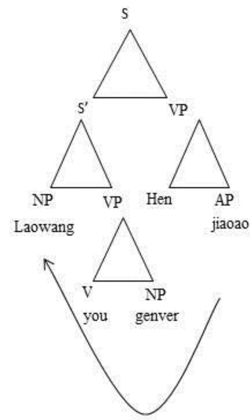
S
S'
VP
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Laowang
VP
Hen
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V
you
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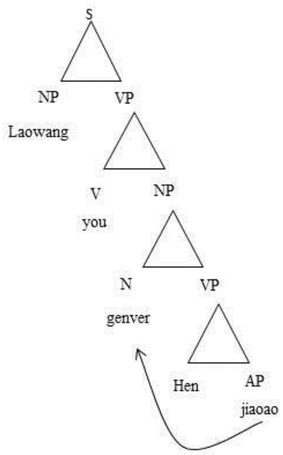
genver


S
NP
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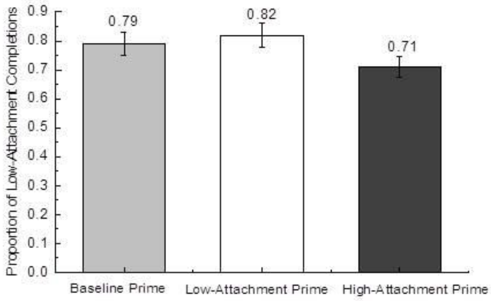
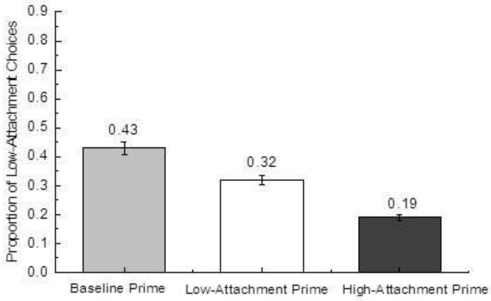
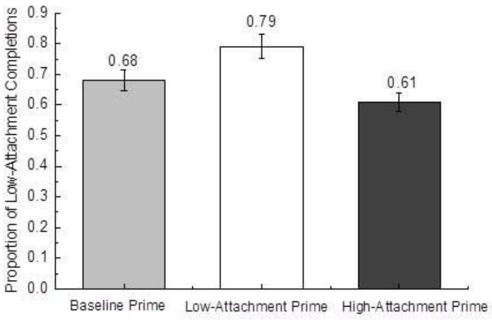
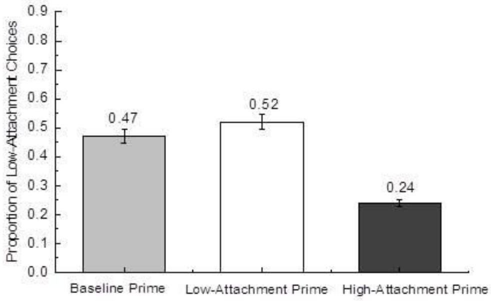

Proportion of Low-Attachment Completions
0.79
0.82
0.71
Baseline Prime
Low-Attachment Prime
High-Attachment Prime


Proportion of Low-Attachment Choices
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.43
0.32
0.19
Baseline Prime
Low-Attachment Prime
High-Attachment Prime


Proportion of Low-Attachment Completions
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.68
0.79
0.61
Baseline Prime
Low-Attachment Prime
High-Attachment Prime


Proportion of Low-Attachment Choices
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.47
0.52
0.24
Baseline Prime
Low-Attachment Prime
High-Attachment Prime