How the speed of working memory updating influences the on-line thematic processing of simple sentences in Mandarin Chinese

Xiao-qing Li · Yuan-yuan Zheng · Hai-yan Zhao · Jin-yan Xia

Received: 6 January 2014 / Revised: 3 April 2014 / Accepted: 28 April 2014 / Published online: 14 May 2014
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Abstract This ERP study used electrophysiological technique to examine how individual differences in the speed of working memory updating influence the use of syntactic and semantic information during on-line sentence argument interpretation, and the time course of that working memory updating effect. The basic structure of the experimental sentences was “Noun + Verb + adverb + ‘le’ + a two-character word”, with the Noun being the sentence initial argument. This initial argument is animate or inanimate and the following verb disambiguates it as an agent or patient. The results at the initial argument revealed that, the quick-updating group elicited a larger positivity over the frontal cortex (within 500–800 ms post-noun onset) as compared with the slow-updating group. At the following disambiguating verb, the slow-updating group only showed a word order effect, indicating that the patient-first condition elicited a larger P600 (within 500–1,000 ms post-verb onset) than the agent-first one; for the quick-updating group, at the early stage of processing, the patient-first sentences elicited a larger N400 (within 300–500 ms post-verb onset) than the agent-first ones only when the initial argument was inanimate; however, at the late stage, the patient-first sentences elicited an enhanced P600 (within 800–1,000 ms post-verb onset) only when the initial argument was animate. These results suggested that the speed of working memory updating not only influences the maintenance of sentence argument when the contents of

working memory change but also influences the efficiency of integrating that argument with the verb at a late time point. When integrating the argument with the disambiguating verb, individuals with quick-updating ability can combine multiple sources of information (both noun animacy and word order), and conduct rapid and fine-grained two-stage processing; individuals with slow-updating ability, however, only rely on one dominant source of information types (word order), and conducted slow and course-grained processing.

Keywords Event-related potential · Word order · Animacy · Individual difference · Working memory updating · Thematic processing

Introduction

Human language comprehension in real time requires the rapid and incremental processing of new information (e.g., grammatical/syntactic and semantic information) from the unfolding linguistic input. Working memory, consisting of storage buffers as well as the manipulation processes, is a critical construct in that process. Lots of studies have investigated the relationship between working memory and language comprehension. However, these studies are primarily concerned with the effect of available working memory capacity on language processing, since there are only limited working memory resources to maintain relevant information and manipulate that information. In fact, good use of working memory involves not only maintaining as much information as possible but also continuously and rapidly updating this information (e.g., Carretti et al. 2005). During on-line language comprehension, the reader/listener is continuously required to eliminate information

X. Li (✉) · Y. Zheng · H. Zhao · J. Xia
Key Laboratory of Behavioral Science, Institute of Psychology,
Chinese Academy of Sciences, No. 16 Lincui Road, Chaoyang
District, Beijing 100101, People's Republic of China
e-mail: lixq@psych.ac.cn

Y. Zheng · H. Zhao · J. Xia
University of Chinese Academy of Sciences, Beijing, China

no longer necessary while bringing in new information to replace it. For example, to understand the garden-path sentences, such as “While the scientists explored the cave remained undiscovered”, the reader must rapidly update the syntactic representations in the working memory. That is, the ability of working memory updating should play an important role in language comprehension. Working memory updating is the act of modifying the content of working memory to accommodate new input, which is one of the executive components underlying management of working memory (Carretti et al. 2005; Miyake et al. 2000; Palladino et al. 2001). In the field of neuroscience, the executive processes of working memory have been subdivided into different component functions: shift attention within working memory (shifting), prevent irrelevant information from becoming active in working memory (inhibition or interference resolution), and updating the contents of working memory (updating) (e.g., Smith and Jonides 1999; Miyake et al. 2000; Friedman and Miyake 2004; Nee et al. 2007, 2013; Bledowski et al. 2010). The present study focused on the updating function of working memory and aimed to investigate how individual differences in the speed of working memory updating affect the on-line process of sentence argument interpretation.

The role of word order and noun animacy in thematic processing

One important aspect of the sentence comprehension process involves establishing the thematic relationship between the verb and its noun arguments, and thereby determining the thematic roles of the arguments. For example, the processors need to decide whether a noun argument is the actor (agent-like role) or the undergoer (patient-like role) of the event being described by the verb. In the field of psycholinguistics, the extended Argument Dependency Model (eADM) (Bornkessel and Schlesewsky 2006; Bornkessel-Schlesewsky and Schlesewsky 2008, 2009a, Bornkessel-Schlesewsky et al. 2009b) has been put forward to explain the process of argument interpretation. According to this model, at the relatively early stage of processing (*compute prominence* and *compute linking*), the language processing system assigns the actor and undergoer roles by referring to morphosyntactic cues (e.g., word order and case) and prominence cues. Prominence cues strongly correlate with generalized semantic roles: actor arguments tend to be more prominent (e.g., animate, definite, and pronominal) than undergoer arguments (e.g., inanimate, indefinite, and lexical). Once the verb is reached, these role assignments are linked to the verb’s lexical entry. At the relatively later stage of processing (*generalized mapping*), other interpretively relevant

information types, such as plausibility, are integrated with the prominent and morphosyntactic cues in order for full argument interpretation to be accomplished.

Previous studies have investigated the role of word order and noun animacy in interpreting the thematic roles of sentence arguments. On the one hand, some studies found a subject-preference effect, namely a general tendency to analyze an ambiguous initial argument as the subject of the sentence (usually the sole argument or the more agent-like argument of the sentence). This subject-preference is well established in Indo-European languages (e.g., Schlesewsky et al. 2003; Penolazzi et al. 2005; Casado et al. 2005) and other languages such as Turkish (Demiral et al. 2008), Basque (Erdocia et al. 2009), Japanese (Wolff et al. 2008), and Mandarin Chinese (Wang et al. 2009). On the other hand, noun animacy also influences the process of thematic role assignment. Some behavioral results indicated that the animate nouns are more ideal agents because they can be volitional initiators of actions, while inanimate nouns are more ideal patients (e.g., Frazier and Rayner 1982; Ferreira and Clifton 1986; Trueswell et al. 1994; Traxler et al. 2002). ERP studies on English simple sentence also revealed that an inanimate sentence-initial argument elicited a larger N400 as comparison to an animate argument filling that position (e.g., Weckerly and Kutas 1999; Nakano et al. 2010), which suggested that animate arguments are more easily assigned the actor role than inanimate arguments. Although ERP results in German (Schlesewsky and Bornkessel 2004), Turkish (Demiral et al. 2008), and Chinese (Philipp et al. 2008) revealed no differences between inanimate and animate initial arguments, they did show effects of animacy when two or more arguments must be interpreted relative to one another. Overall, those studies demonstrated that both word order and noun animacy play an important role in the process of argument interpretation.

The effect of working memory on sentence processing

Different accounts have been put forward to explain how working memory affects language processing (e.g., Just and Carpenter 1992; Lewis and Vasishth 2005; Lewis et al. 2006). Here, we will introduce two accounts which are related to the present study. First, one widely accepted view is the *shared resource* account put forward by Just and Carpenter (Just and Carpenter 1992). According to this account, during language comprehension, information maintenance and manipulation draw upon a single pool of working memory resources (of activation). If manipulation function uses a lot of activation resources, then less will be available for maintenance of linguistic information. Secondly, according to the computational principles of working memory put forward by Lewis and colleagues

(Lewis and Vasishth 2005; Lewis et al. 2006), working memory has a sharply limited attentional focus, and sentence processing is underlined by rapid cue-based working-memory retrieval. This cue-based parsing carves up working memory processes into stages of encoding, storage, and retrieval. Once the previous information was retrieved and integrated with the current information, working memory is updated with the encoding of new information (Lewis and Vasishth 2005; Lewis et al. 2006). Therefore, both accounts indicated that the efficiency of information manipulation, including updating, should play a very important role in sentence comprehension, since there are limited working memory resources or limited attentional focus. An interesting question is how individual updating difference may influence the use of the multiple sources of linguistic cues, and influence the different stages of information processing during on-line sentence comprehension.

Previous studies on working memory and sentence processing mainly focused on how individual differences in working memory capacity (as assessed with a reading span test) influence sentence comprehension. First, results of some ERP studies showed that the ERP effect elicited by syntactic structure variation differed between the high- and low-capacity individuals (e.g., Bornkessel et al. 2004; Domenico et al. 2010; Friederici et al. 1998; Fiebach et al. 2002; King and Kutas 1995; Vos et al. 2001). For example, only for reader with high working memory capacity, complex object-first relatives elicited larger P350-P600 as compared with simple subject-first relatives (Friederici et al. 1998). Secondly, some studies revealed that, relative to the low-capacity group, the high-capacity group is more able to use animacy information to understand the meaning of the sentences (e.g., Long et al. 2008; Nakano et al. 2010; Traxler et al. 2005). For example, Nakanol and colleagues compared sentences that involve animacy violation (*The box was biting the mailman*) with non-anomalous sentences (*The dog is biting the mailman*). They found that the high-capacity subjects showed effects of animacy both on the sentence-initial nouns and on the following verb; the low-capacity subjects, however, only showed an ERP effect on the verb. The results suggested that the low-capacity subjects lag behind those with high capacity in their use of animacy in thematic processing (Nakano et al. 2010). Overall, individual differences in working memory capacity influence not only the sensitivity to syntactic structure variations but also the sensitivity to the noun animacy information.

Only a few studies have directly examined the effect of working memory updating on language comprehension (Carretti et al. 2005; Palladino et al. 2001). For example, Palladino et al. (2001) examined the relationship between reading comprehension skill and updating in working

memory. They used a keep-track task to measure the working memory updating ability of the participants. For example, the participants were asked to recall the last four letters in lists of consonants of varying length. The results showed that participants with low reading comprehension ability not only had poorer recall in the keep-track task, but also made more intrusion errors than did good comprehenders. Subsequently, Carretti et al. (2005) also found that, while conducting a keep-track task, poor comprehenders were more likely to intrude items that were maintained longer in memory than were good comprehenders. Those results suggested that the difficulties in working memory updating—especially the inability to inhibit information that is no longer relevant—impede reading comprehension.

In summary, quite a lot of studies have investigated the relationship between working memory and language comprehension. However, most of these studies focused on the effect of working memory capacity on sentence processing (e.g., Bornkessel et al. 2004; Domenico et al. 2010; Friederici et al. 1998; King and Kutas 1995; Long et al. 2008; Nakano et al. 2010; Traxler et al. 2005). Even though some studies examined the role of working memory updating in language comprehension, they were mainly concerned with the inhibit function of working memory and its correlation with reading comprehension skills as revealed by some off-line measures (Carretti et al. 2005; Palladino et al. 2001). In fact, real-time language comprehension requires the rapid and incremental processing of novel information. Therefore, the speed of working memory updating would also play a very important role in language comprehension. As mentioned in the early section, working memory updating is a very important component function of the executive processes of working memory. Until now, it's still unclear how the individual differences in the speed of working memory updating influence language comprehension, especially the on-line process of language comprehension. As mentioned in the early part of the introduction section, sentence argument interpretation is based on both syntactic (e.g., word order) and semantic (e.g., animacy) cues, and is conducted in two stages (e.g., computing prominence and computing linking in the early stage and generalized mapping in the later stage). Meanwhile, except for its retrieval and integration with the verb, argument processing also includes its encoding and maintaining in the preceding part of the sentence, as indicated by the working memory theory put forward by Lewis and colleagues (Lewis and Vasishth 2005; Lewis et al. 2006). We don't know how the speed of working memory updating influences the combining of the different sources of linguistic information during on-line sentence argument interpretation, and how the effect of working memory updating changes along the time course of thematic processing (e.g., noun argument encoding,

storage, retrieval, and integration with the following verb). Answering these questions would not only help to understand the processing of argument interpretation but also help to shed new lights on our understanding of how working memory may influence language comprehension.

Therefore, the aim of the present study was to investigate how the individual differences in the speed of working memory updating influence the combining of the different sources of linguistic information during on-line thematic processing of simple sentences. Meanwhile, we aimed to investigate the time course of that working memory updating effect. That is, how the speed of working memory updating influences the different processing stages of sentence argument interpretation.

To address these questions, the EEG technique was used due to its high temporal resolution. In a number of recent ERP studies, thematic roles disambiguation has been shown to correlate with N400 effects or P600 effects. The N400 effect has a central-parietal or frontal distribution and occurs in the time range around 300–500 ms after the onset of the disambiguating verb. This N400 can be viewed as a correlate of an argument linking mismatch, which arises when the argument hierarchy that was established prior to the verb cannot be straightforwardly mapped (linked) onto the lexical representation of the verb. The P600 effect has a broad or central-parietal distribution and occurs in a time range from approximately 500 to 1,000 ms post-critical stimulus onset, which is considered to reflect the cost of reanalysis process or well-formedness evaluation when required (Bornkessel-Schlesewsky et al. 2004; Bornkessel and Schlewsky 2006; Friederici and Mecklinger 1996; Haupt et al. 2008; Wolff et al. 2007). In addition, more recent studies found that frontal late positive potentials (frontal P600) are elicited during the interpretation of plausible sentence completions, which are considered to reflect the manipulation of information in working memory (such as inhibition of a predicted-but-not-presented word) (see review for Van Petten and Luka 2012). Therefore, the ERP components of interest in the present study are the N400 and P600 components.

In the present study, native speakers were asked to read simple Mandarin Chinese sentences for comprehension. The basic structure of the sentences is “Noun + adverb + Verb + ‘le’ + a two-character word”, with the Noun being an ambiguous sentence-initial argument. The Verb disambiguates the Noun as an actor or undergoer of the event being described. Meanwhile, the Noun in the sentence is animate or inanimate. By examining the ERPs time-locked the Nouns, we would know how the speed of working memory updating affects the encoding and maintaining of sentence argument; by examining the ERPs time-locked the Verbs, we would know how the speed of working

memory updating influences the combining of the different sources of linguistic information when the argument was retrieved and integrated with the verb.

Methods

Participants

30 university students took part in this EEG experiment for cash. All participants are native speakers of Mandarin Chinese. All of them had normal or normal-to-corrected vision, were right-handed and neurologically healthy. The participants were pre-selected on the basis of their individual speed of working memory updating, and were assigned to two groups: a quick-updating group of 15 participants (6 males, 20–26 years) and a slow-updating group of 15 participants (7 males, 20–25 years).

In the present study, we used one version of *n*-back task, namely a verbal 2-back task, to measure the working memory updating ability of the participants. Although both keep-track task and *n*-back task measure the ability of working memory updating (Ecker et al. 2010), the latter more emphasizes the speed of working memory updating (e.g., Miller et al. 2009; Parmenter et al. 2006; Oberauer 2005).

The verbal 2-back task used in the present study had 96 trials. For each trial, a letter appeared for 500 ms and was followed by a blank-screen inter-trial interval of 2,000 ms. The participants were instructed to press one of two keys to indicate whether a letter matches the letter that appeared two items previously in the series. Reaction time and accuracy were recorded for each trial. 68 university students participated in this 2-back task experiment. To exclude the possibility of speed-accuracy tradeoff, 18 students, whose accuracy rate was less than 80 %, were deleted (the deleted students were almost evenly distributed among the different speed of responses). Then, for the remaining 50 students, based on their reaction time, the top 30 % (15 students) and the bottom 30 % (15 students) students were selected for the quick- and slow-updating group respectively. The reaction time and accuracy rate for the selected quick-updating and slow-updating groups were 679.60 ms (SD = 100.22) with an average accuracy rate of 93.33 % (SD = 5.39) and 1,110.13 ms (SD = 130.43) with an average accuracy rate of 90.22 % (SD = 5.13), respectively. The T test revealed that reaction times for the quick-updating group were significantly shorter than those for the slow-updating group ($t_{(28)} = 10.14, p \leq .0001$); in contrast, there was no significant difference in the accuracy rate of these two groups ($t_{(28)} = 1.72, p = .097$).

Table 1 The basic structure of the experimental sentences

Conditions	Example (Noun +adverb +Verb +‘le’ +a two-character word)
1. aAV	蚊子/已经/叮咬/了/表弟. Mosquito/already/ <u>bite</u> /'le'/cousin The mosquito has already <u>bitten</u> my cousin
2. aPV	蚊子/已经/消灭/了/一群. Mosquito/already/ <u>eliminate</u> /'le'/a group A group of mosquitoes has already been <u>eliminated</u>
3. inAV	毒品/已经/伤害/了/身体. Drug/already/ <u>hurt</u> /'le'/body The drug has already <u>hurt</u> someone's body
4. inPV	毒品/已经/销毁/了/一些. Drug/already/ <u>destroy by burning</u> /'le'/some Some drugs have already been <u>destroyed by burning</u>

aAV indicates ‘animate, agent-first’; aPV indicates ‘animate, patient-first’; inAV indicates ‘inanimate, agent-first’; inPV indicates ‘inanimate, patient-first’. The underlined words are the critical words (Verb)

Stimuli

In the present study, 80 pairs of Mandarin Chinese sentences were constructed. The basic structure of these sentences is “Noun + adverb + Verb + ‘le’ + a two-character word”, with the Noun being an sentence-initial argument. The thematic role of this initial argument is ambiguous, since Mandarin Chinese has an impoverished morphological system (such as case markers) and relatively free word-order. The word ‘le’ is an auxiliary word, which indicates that the action demoted by the verb has already happened. The Nouns, the Verbs, and the adverbs (such as ‘finally’, ‘just now’, ‘maybe’, and ‘certainly’) between the Noun and the Verb are all double-character words. On the one hand, every pair of sentences had the same Noun (initial argument): for 40 pairs of sentences, the Noun was animate; for the other 40 pairs of sentences, the Noun was inanimate (animate vs. inanimate). On the one hand, every pair of sentences had different Verbs: the Verb disambiguates the Noun as an actor or an undergoer of the event being described (agent-first vs. patient-first). Together, they realized a full factorial design with all combinations of the factors Word order and Animacy (see Table 1). In addition, we added a time adverbial (or a place adverbial) preceding the basic sentence structure to prevent the Noun appearing at the beginning of the sentence. Both the adverbs at the beginning of the sentence and the adverbs between the Noun and the Verb were counterbalanced between the four experimental conditions.

In Mandarin Chinese, the basic word order is ‘Subject + Verb + Object’ (namely, Agent + Verb + Patient).

Like Italian and Turkish, Chinese permits subject-drop. When the agent is not coded, at the requirement of information distribution, or rather, driven by Topic, the patient argument is moved to the sentence initial position, resulting in the “Patient + Verb + ...” sentence (Wang, Wang et al. 2008). Even though no passive morphology is used, the “Patient + Verb + ...” construction can indicate the passive relations semantically, since Chinese is a paratactic language, valuing the semantic coherence instead of the formal cohesion as in English (Liu, 1994). Moreover, in the present study, the two-character verbs are all verb-complement compound (e.g., 拧坏 screw-broken) or sequential-verb compound (e.g., 销毁 destroy) (These two kinds of verbs were counter-balanced between the different experimental conditions). The first character in the verb-complement compound is a verb and the second one is a complement describing the state caused by the verb. The two characters in the sequential-verb compound are all verbs which have similar meaning, with the former emphasizing the action and the latter emphasizing the result. That is, both kinds of compound verbs emphasize the following two aspects: the action initiated by the implicit (or explicit) agent and the state of the patient caused by that action. Therefore, the characteristics of Mandarin Chinese as well as the verbs we used suggested that, in the present study, the initial argument in the “patient-first” sentence is indeed disambiguated as the patient of the verb.

To confirm that the Noun was indeed interpreted as an actor (agent-like) or an undergoer (patient-like), 20 participants who didn’t attend the EEG experiment were asked to mark the thematic role of the Nouns on a 5-point scale (from –2 to 2). The participants were just presented with the pairs of Noun and Verb. –2 indicated that the Noun was absolutely interpreted as an undergoer; 2 indicated that the Noun was absolutely interpreted as an actor. The ANOVAs with Word order and Animacy as independent factors revealed that the rating score for the agent-first condition was larger than that for the patient-first condition ($F(1,78) = 963.45, p < .0001$, see Fig. 1a). The effect of Animacy or the two-way Word order $\times$ Animacy interaction didn’t reach significance (all $ps > .1$). The results indicated that the manipulation of word order was successful.

Another 20 participants were asked to mark the semantic relatedness between the Noun and Verb on a 5-point scale (from –2 to 2). –2 indicated that the pair of words was not semantically related; 2 indicated that the pair of words was highly semantically related. The ANOVA with the rating score as dependant factor revealed that neither the main effect of word order (or animacy) nor the interaction between them reached significance (all $ps > .1$, see Fig. 1b). In addition, the word frequency (according to the

Fig. 1 a (Argument interpretation pre-test): -2 indicated that the Noun was absolutely interpreted as an undergoer; 2 indicated that the Noun was absolutely interpreted as an actor. **b** (Semantic relatedness pre-test): -2 indicated that Noun and Verb were not semantically

related; 2 indicated that Noun and Verb were highly semantically related. *aAV* indicates 'animate, agent-first'; *aPV* indicates 'animate, patient-first'; *inAV* indicates 'inanimate, agent-first'; *inPV* indicates 'inanimate, patient-first'

Fig. 2 Word frequency and number of strokes of the critical words (Nouns and Verbs). *aAV* indicates 'animate, agent-first'; *aPV* indicates 'animate, patient-first'; *inAV* indicates 'inanimate, agent-first'; *inPV* indicates 'inanimate, patient-first'

Modern Chinese Frequency Dictionary, 1986) ($t_{(78)} = .431$, $p = .668$) and the numbers of strokes ($t_{(78)} = .219$, $p = .827$) of animate Nouns were not different from those of inanimate Nouns. The ANOVAs with both word frequency and number of strokes of the Verbs as dependant factors also revealed no significant effect (see Fig. 2). Therefore, neither the semantic relatedness nor the word frequency and the number of strokes were confounding factors.

The participants read all of the experimental sentences (totally 160 sentences with 40 sentences for each of the four conditions). In addition, there were also 108 filler sentences. For the filler sentences, many kinds of sentence structure were used in order to prevent the participants detecting the aims of the experiment.

Procedure

After the electrodes were positioned, participants were asked to read each sentence for comprehension. Meanwhile, their EEG signals were recorded. Each trial started with a fixation "+" (duration of 1,000 ms) in the center of the screen. After the fixation, the sentence was presented word by word (e.g., the sentence-initial adverb + Noun + adverb + Verb + 'le' + sentence-final word; that is, the auxiliary word 'le' was presented as a separate word), with each word appearing for 300 ms, with an inter stimulus interval of 300 ms (namely, stimulus-onset asynchrony of 600 ms). To ensure that the participants indeed read the sentences for comprehension, at the end of each of the 144 sentences in all of the materials, they were asked to judge

Fig. 3 Grand-average ERPs time-locked to the Nouns in the animate and inanimate conditions. Quick-updating group elicited a larger P600 over the frontal electrodes (within 500–800 ms post-noun onset) than the slow-updating group

the correctness of a question sentence regarding the meaning of the sentence just read. After a short practice session consisting of ten sentences, the trials were presented in four blocks of about 30 min totally.

EEG acquisition

EEG was recorded (.05–100 Hz, sampling rate 500 Hz) from 64 Ag/AgCl electrodes mounted in an elastic cap, with an on-line reference linked to the left mastoid and off-line algebraic re-reference linked to the left and right mastoids. EEG and EOG data were amplified with AC amplifiers (Synamps, Neuroscan Inc.). Vertical eye movements were monitored via a supra- to sub-orbital bipolar montage. A right-to-left canthal bipolar montage was used to monitor horizontal eye movements. All electrode impedance levels (EEG and EOG) were kept below 5 k Ω .

Data preprocessing

For ERP analysis, the raw EEG data were first corrected for eye-blink artifacts and filtered with a band-pass filter .1–40 Hz. Subsequently, the filtered data were divided into epochs ranging from 100 ms before the onset of the critical words to 1,000 ms (or 1,200 ms) after the onset of the critical words. A time window of 100 ms preceding the onset of the critical words was used for baseline correction. Trials contaminated by eye movements, muscle artifacts, electrode drifting, amplifier saturation, or other artifacts were identified with a semiautomatic artifact rejection (automatic criterion: signal amplitude exceeding ± 75 uV, followed by a manual check). Trials containing the abovementioned artifacts were rejected (12.5 % overall). Rejected trials were evenly distributed among conditions. Finally, averages were computed for each participant, each

Fig. 4 Grand-average ERPs time-locked to the Verbs in the four experimental conditions for the quick-updating participants. Relative to the Agent-first condition, the Patient-first condition elicited a larger

N400 (within 300–500 ms and 500–800 ms post-verb onset) when the initial argument was inanimate, and elicited a larger P600 (within 800–1,000 ms post-verb onset) when the initial argument was animate

condition, and at each electrode site before grand averages were calculated across all participants.

Figure 3 showed overlays of the ERP waveforms time-locked to the Nouns in the animate and inanimate conditions. Around 500–800 ms after the onset of the Noun (post-noun onset), the quick-updating group elicited a larger positive deflection than the slow-updating group over the frontal electrodes.

Figures 4 and 5 showed overlays of the ERP waveforms time-locked to the Verbs in the four conditions. For the quick-updating group (see Fig. 4), relative to the agent-first condition, the patient-first condition evoked a larger P600 (around in 800–1,000 ms post-verb onset) when the initial argument was animate, and elicited a larger negative deflection when the initial argument was inanimate. This negativity effect peaked around 350 ms after the onset of

the Verb and had a frontal-central distribution. We classified this negativity effect as a N400 effect, since previous studies had observed the same frontally-centrally distributed N400 effect (Balconi and Caldiroli 2011; Nakano et al. 2010). For the slow-updating group (see Fig. 5), around in the window latency of 500–1,000 ms after the onset of the Verb (post-verb onset), the patient-first condition elicited a larger P600 than the agent-first one.

Statistical analysis

For the ERPs time-locked to the Verbs, statistical analyses were done on the mean amplitude in the 180–240 ms (for P2 effect), 300–500 ms (for N400 effect), 500–800 ms, and 800–1,000 ms (for P600 effect) latency ranges following the onset of the Verbs. Analyses of variance were

Fig. 5 Grand-average ERPs time-locked to the Verbs in the four experimental conditions for the slow-updating participants. Relative to the Agent-first condition, the Patient-first condition elicited a larger

P600 (within 500–1,000 post-verb onset) regardless of the animacy properties of the initial argument

conducted on a selection of midline electrodes and lateral electrodes respectively. For the midline electrode sites, the mean amplitude values were entered into ANOVAs with Group (quick-updating vs. slow-updating), Word order (agent-first vs. patient-first), Animacy (animate vs. inanimate), and Anteriority (frontal: Fz; central: Cz; parietal: Pz) as independent factors. For lateral electrodes, the mean amplitude values were entered into ANOVAs with Hemisphere (left, right) as an additional factor and lateral electrodes (F5/F3/FC3; F4/F6/FC4; C5/C3/CP3; C4/C6/CP4; P5/P3/PO3; P4/P6/PO4) nested under Hemisphere.

For the ERPs time-locked to the Nouns, statistical analyses were done on the mean amplitude in the 180–240 ms, 300–500 ms, 500–800 ms, 800–1,000 ms, and 1,100–1,200 ms latency ranges following the onset of the Nouns. The 1,100–1,200 ms window latency corresponded to the baseline interval for the ERPs time-locked to the

Verb. The ANOVAs for the Noun were the same as those for the Verb except that the independent factors didn't include Word order.

When the degree of freedom in the numerator was larger than one, the Greenhouse-Geisser correction was applied. When interactions with group occurred, follow-up analyses were performed for quick-updating and slow-updating participants respectively.

Results

Behavioral results

For all participants, the accuracy rate of the question sentence was higher than 90 %; and the accuracy rate of the quick-updating group was not different from that of the

slow-updating group ($t_{(28)} = .386$, $p = .420$; Mean accuracy rate: 94.2 and 94.5 % for the quick- and slow-updating groups respectively).

ERP results at the Noun (sentence-initial argument)

As seen from Fig. 3, the ANOVA for the 180–240 ms latency window resulted in a significant two-way Animacy $\times$ Anteriority interaction over the lateral electrodes ($F_{lateral}(2,56) = 9.83$, $p < .005$, $MSE = .65$). Further simple analysis found that the animacy effect reached significance over none of the brain areas ($F_{lateral}(1,28) = 3.36$, $p = .078$, $MSE = 2.35$; $F_{lateral}(1,28) = 1.67$, $p = .206$, $MSE = 2.02$; $F_{lateral}(1,28) = .57$, $p = .458$, $MSE = 1.50$ for the frontal, central, and parietal areas respectively).

The ANOVAs in the 300–500 ms window latency resulted in neither significant main effects of Animacy (or Group) nor their interaction with other factors (see Fig. 3).

In the 500–800 ms window latency, the ANOVAs revealed a significant two-way Group $\times$ Anteriority interaction over the lateral electrodes ($F_{lateral}(2,56) = 4.48$, $p < .05$, $MSE = 3.76$). Further analysis showed that the quick-updating group elicited marginally significant larger positive deflection than the slow-updating group over the frontal electrodes ($F_{lateral}(1,28) = 3.92$, $p = .058$, $MSE = 7.34$) (see Fig. 3).

In both 800–1,000 ms and 1,100–1,200 ms window latencies, the ANOVAs resulted in neither significant main effects of Animacy (or Group) nor their interaction with other factors (all $ps > .1$). The 1,100–1,200 ms window latency corresponded to the baseline interval for the ERPs time-locked to the Verb. These results indicated that, the ERP waveforms didn't show significant difference in the baseline interval for the Verb.

ERP results at the Verb

The ANOVA for the 180–240 ms window latency revealed a significant three-way Word order $\times$ Anteriority $\times$ Hemisphere interaction over the lateral electrodes ($F_{lateral}(2,56) = 4.95$, $p < .05$, $MSE = .10$). Further simple analysis found that the effect of Word order reached significance over none of the six brain areas (all $ps > .1$) (see Figs. 4 and 5).

In the 300–500 ms window latency, the ANOVAs revealed a significant four-way Group $\times$ Word order $\times$ Animacy $\times$ Hemisphere interaction ($F_{lateral}(1,28) = 7.20$, $p < .05$, $MSE = .76$). Over the midline electrodes, there is a trend toward significance for the three-way Group $\times$ Word order $\times$ Animacy interaction ($F_{midline}(1,28) = 3.25$, $p = .079$, $MSE = 4.55$). We performed statistic analyses for the quick-updating and slow-updating groups

respectively. First, for the quick-updating group (see Fig. 4), the ANOVAs resulted in a significant two-way Word order $\times$ Animacy interaction ($F_{midline}(1,14) = 11.16$, $p < .005$, $MSE = 2.73$; $F_{lateral}(1,14) = 8.76$, $p < .01$, $MSE = 3.50$). Further simple analysis found that the patient-first condition elicited a significant larger N400 than the agent-first condition when the initial argument was inanimate ($F_{midline}(1,14) = 7.92$, $p < .05$, $MSE = 3.59$; $F_{lateral}(1,14) = 7.16$, $p < .05$, $MSE = 3.92$); in contrast, when the initial argument was animate, there was no significant difference between the patient-first and agent-first conditions ($F_{midline}(1,14) = 1.11$, $p = .310$, $MSE = 5.53$; $F_{lateral}(1,14) = .90$, $p = .358$, $MSE = 7.13$). In addition, the quick-updating group showed a significant two-way Animacy $\times$ Anteriority interaction ($F_{midline}(2,28) = 9.33$, $p < .005$, $MSE = .47$; $F_{lateral}(2,28) = 12.26$, $p < .001$, $MSE = .54$). Further simple analysis revealed that the inanimate condition elicited a larger N400 than the animate condition over the frontal electrodes ($F_{midline}(1,14) = 5.21$, $p < .05$, $MSE = 2.36$; $F_{lateral}(1,14) = 7.09$, $p < .05$, $MSE = 2.73$). Second, for the slow-updating group (see Fig. 5), the ANOVAs only results in a significant three-way Word order $\times$ Animacy $\times$ Hemisphere interaction over the lateral electrodes ($F_{lateral}(1,14) = 4.91$, $p < .05$, $MSE = .87$). Further analysis revealed that, both in the animate and inanimate conditions, the effect of word order reached significance at neither the left nor the right hemisphere (all $ps > .1$).

The ANOVA for the 500–800 ms window latency resulted in a significant three-way Group $\times$ Word order $\times$ Animacy interaction ($F_{midline}(1,28) = 5.97$, $p < .05$, $MSE = 4.43$; $F_{lateral}(1,28) = 4.46$, $p < .05$, $MSE = 5.53$). First, for the quick-updating group (see Fig. 4), the two-way Word order $\times$ Animacy interaction reached significance ($F_{midline}(1,14) = 12.36$, $p < .005$, $MSE = 2.80$; $F_{lateral}(1,14) = 6.70$, $p < .05$, $MSE = 4.73$). Further simple analysis found that, when the initial argument was inanimate, the patient-first condition elicited a larger negative deflection than the agent-first condition ($F_{midline}(1,14) = 10.31$, $p < .01$, $MSE = 2.92$; $F_{lateral}(1,14) = 8.07$, $p < .05$, $MSE = 3.13$); in contrast, when the initial argument was animate, there was no significant difference between the patient-first and agent-first conditions ($F_{midline}(1,14) = 2.19$, $p = .161$, $MSE = 3.68$; $F_{lateral}(1,14) = 1.40$, $p = .257$, $MSE = 6.17$). Second, for the slow-updating group (see Fig. 5), the ANOVAs resulted in a significant Word order $\times$ Anteriority interaction ($F_{midline}(2,28) = 4.21$, $p < .05$, $MSE = .87$; $F_{lateral}(2,28) = 7.18$, $p < .01$, $MSE = .53$). Further analysis found that the patient-first condition elicited a marginally significant larger positive deflection than the agent-first condition over the lateral-parietal electrodes ($F_{midline}(1,14) = 3.19$, $p = .096$,

Fig. 6 Results of the regression analyses for the mean amplitude of the N400 effect (word order effect when the initial argument was inanimate) at the Verbs as a function of working memory scores for each individual in the quick- and slow-updating groups. The amplitude (μV) and the reaction time of the verbal 2-back task are displayed on the vertical and horizontal axis, respectively

$MSE = 1.93$; $F_{\text{lateral}}(1,14) = 4.36$, $p = .056$, $MSE = 2.50$).

The ANOVA for the 800–1,000 ms window latency showed that there was a significant three-way Group $\times$ Word order $\times$ Animacy interaction ($F_{\text{midline}}(1,28) = 6.79$, $p < .05$, $MSE = 5.89$; $F_{\text{lateral}}(1,28) = 5.57$, $p < .05$, $MSE = 7.98$). First, for the quick-updating group (see Fig. 4), the ANOVAs revealed a significant two-way interaction between Word order and Animacy ($F_{\text{midline}}(1,14) = 8.21$, $p < .05$, $MSE = 6.30$; $F_{\text{lateral}}(1,14) = 6.82$, $p < .05$, $MSE = 8.92$). Simple analysis showed that, when the initial argument was animate, the patient-first condition elicited a larger P600 than the agent-first condition ($F_{\text{midline}}(1,14) = 8.44$, $p < .05$, $MSE = 5.10$; $F_{\text{lateral}}(1,14) = 7.17$, $p < .05$, $MSE = 7.74$); in contrast, there was no significant difference between the patient-first and agent-first conditions when the initial argument was inanimate ($F_{\text{midline}}(1,14) = 2.35$, $p = .147$, $MSE = 5.51$; $F_{\text{lateral}}(1,14) = 2.07$, $p = .173$, $MSE = 6.22$). Second, for the slow-updating group (see Fig. 5), the ANOVAs revealed a significant Word order $\times$ Anteriority interaction ($F_{\text{midline}}(2,28) = 6.66$, $p < .05$, $MSE = 1.60$; $F_{\text{lateral}}(2,28) = 18.82$, $p < .001$, $MSE = .61$). Further analysis found that the patient-first condition elicited a significantly larger P600 than the agent-first condition over the parietal electrodes ($F_{\text{midline}}(1,14) = 6.85$, $p < .05$, $MSE = 4.74$; $F_{\text{lateral}}(1,14) = 7.11$, $p < .05$, $MSE = 6.76$).

Correlation analysis

The regression analyses were performed to further examine the relation between the speed of working memory updating and the word order effect (N400 effect) at the verb when the initial argument was inanimate. Figure 6 showed that quick working memory updating scores were

correlated with greater N400 effect (word order effect) at the verb when the initial argument was inanimate ($r = .35$, $p < .05$).

Discussion

The present study examined how individual differences in the speed of working memory updating affect the on-line process of sentence arguments interpretation. The major results were that, at the initial argument (Noun), the quick-updating group elicited a larger frontal P600 than the slow-updating group around 500–800 ms after the onset of the initial argument. Importantly, at the following disambiguating Verb, the slow-updating group only showed a word order effect, suggesting that the patient-first sentences elicited a larger parietal P600 than the agent-first ones (500–1,000 ms post-verb onset); in contrast, the quick-updating group showed an interaction between word order and animacy within both in early and later time windows. That is, for the quick-updating group, at the early stage of processing (300–500 ms post-verb onset), the patient-first sentences elicited a larger N400 as compared with the agent-first ones only when the initial argument was inanimate; at the later stage of processing (800–1,000 ms post-verb onset), the word order effect reached significance only when the initial argument was animate, reflected as enhanced P600 for the patient-first sentences. These results are discussed in more detail below.

The on-line argument interpretation process in the quick- and slow-updating groups

At the disambiguating verb, the quick- and slow-updating groups showed different patterns of results. What's the cognitive mechanism that underlines those results? The slow-updating group only showed a word-order effect, reflected by the enhanced P600 in the patient-first condition within 500–1,000 ms post-verb onset. As mentioned in the introduction section, the P600 effect has been considered to reflect the cost of reanalysis process or well-formedness evaluation at the later stage of sentence comprehension (Bornkessel and Schleewsky 2006). Therefore, the P600 effect observed here suggested that, for the slow-updating group, word-order information influenced thematic processing only after the noun argument had already been linked to the lexical representation of the verb. That is, in the patient-first condition, disambiguating the initial argument as a patient role resulted in well-formedness violation, hence eliciting an enhanced P600, since there is a tendency to analyze ambiguous initial arguments as the sole argument or the more agent-like argument (namely, subject-preference effect, e.g., Schleewsky et al. 2003;

Demiral et al. 2008; Erdocia et al. 2009; Wolff et al. 2008; Wang et al. 2009). In short, during on-line sentence argument interpretation, the slow-updating group was insensitive to noun animacy and only used word-order information at the later stage of processing.

Different from the slow-updating group, the quick-updating group showed a two-stage processing: at the early stage (reflected by the N400 effect within 300–500 ms post-verb onset), the word order effect reached significance only when the initial argument was inanimate; in contrast, at the late stage (reflected by the P600 effect within 800–1,000 ms post-verb onset), the word order effect appeared only when the initial argument was animate. We think that, it might be that, at the early stage of processing, animacy influences thematic processing through the differences in the conceptual accessibility of animate and inanimate entities. Relative to the animate noun, the inanimate noun is less accessible and is therefore retrieved with more difficulty from memory (Kathryn Bock and Warren 1985; Branigan et al. 2008). Therefore, in the harder situation (inanimate), disambiguating the initial argument as a patient role caused an argument linking mismatch and made a heavy demand on working memory, since there exists a subject-preference phenomenon. So, in the inanimate conditions, the patient-first sentence elicited an enhanced N400 as compared with the agent-first one. However, in the easier situation (animate), the word order variation didn't induce perceived difference; it may be that the working memory demand caused by the unpreferred word order was simply not high enough in the easier situation. In line with this explanation, Fig. 4 suggested that the N400 effect elicited by word order variation was more prominent anteriorly, even though its interaction with electrodes didn't reach significance. The anterior negativity effect has been related to working memory load (e.g., King and Kutas 1995; Kluender and Kutas 1993a; Fiebach et al. 2002). Moreover, the quick-updating group revealed that, at the verb, the inanimate condition elicited a larger negativity over the frontal cortex than the animate condition, which suggested that the inanimate argument was indeed more difficult to retrieve from memory. On the other hand, at a later processing stage, the participants re-compute the thematic role of the sentence arguments (e.g., evaluate the well-formedness of the sentence), and the plausibility of argument animacy (animate arguments are considered more ideal agents and inanimate arguments more ideal patients) is taken into account to interpret the arguments. That is, when the initial argument was animate, both subject-preference and animacy properties of argument predicted that the patient-first sentence was less preferred, hence the patient-first sentence eliciting an enhanced P600. However, when the initial argument was inanimate, the prediction of argument animacy properties was different

from that of subject-preference, which might cancel out the word order effect, hence no P600 effect being observed in the inanimate conditions. The two-stage processing observed for the quick-updating group was consistent with our recent eye-tracking experiment (Li et al., in revision) that investigated how and when word order and noun animacy interact with each other during on-line thematic processing of Mandarin Chinese sentences. In that eye-tracking experiment, the experimental sentence included an ambiguous initial argument (animate or inanimate) and a following disambiguating verb (disambiguating the initial argument as an agent or patient); different from the present study, the participants in the eye-tracking study were randomly recruited and not divided into different groups. The eye-tracking results showed that, for the early processing stage as indicated by gaze duration (first-pass time, the total time of all the fixations spent in a region before exiting to the left or right), the patient-first sentences needed longer time to process than the agent-first ones only when the initial argument was inanimate; in contrast, for the later processing stage as indicated by the second-pass time (the total time of all fixations that are made on the region after the region has been fixated and exited for the first time), the subject-preference effect appeared only when the initial argument was animate (Li et al., in revision). That is, the two-stage of argument interpretation found in the early eye-tracking study was observed for the quick-updating group in the present study. In short, the quick-updating group showed a pattern of two-stage processing: at the early stage of processing, the conceptual accessibility of animate/inanimate arguments, combined with word order, influenced the difficulty of linking the argument to the verb; at the later stage of processing, the plausibility of argument animacy and word order might be used to re-compute the thematic role of the sentence arguments.

How individual differences in the speed of working memory updating influence the on-line process of sentence argument interpretation

The present study mainly focused on the relationship between the individual differences in the speed of working memory updating and sentence argument interpretation. As mentioned in the introduction, Lewis and colleagues (Lewis and Vasishth 2005; Lewis et al. 2006) carve up working memory processes that subserve sentence comprehension into stages of encoding, storage, and retrieval. First, the present study revealed that, at the initial argument, the quick-updating group showed a larger positivity over the frontal cortex (500–800 ms post-noun onset) as compared with the slow-updating group. The later frontal positivity has been found to be elicited during interpretation of plausible sentence completions, and is considered to reflect the manipulation of information in working memory

(e.g. Van Petten and Luka 2012). In the present study, within 500–800 ms post-noun onset, the following adverb had been presented, since the stimulus-onset asynchrony was 600 ms. The enhanced frontal positivity observed in the quick-updating group might be due to the fact that the quick-updating group can allocate more working memory resources for maintaining the important information, namely the sentence initial argument, when new information is introduced into working memory. Secondly, when the disambiguating verb was presented, the participants need to retrieve the ambiguous initial argument and integrated it with the verb. The most important aim of the present study was to investigate, at the disambiguating verb, how the speed of working memory updating influences the combining of the different sources of linguistic information to interpret the sentence argument. The present results revealed that, at the disambiguating verb, the quick-updating group can integrate multiple sources of information (namely, both noun animacy and syntactic information such as word order) to interpret the arguments; meanwhile, these different sources of information already take effect at the early stage of processing (*compute prominence* and *compute linking*). In contrast, the slow-updating group was not sensitive to the noun animacy and relied on only the word-order information, which took effect at the later stage of processing (*generalized mapping*). These results suggested that, during sentence argument interpretation, the individual differences in the speed of working memory updating influenced both the weights of the different sources of linguistic information and the speed of using that corresponding information.

Previous studies have already examined the relationship between working memory and sentence processing. For example, some studies indicated that the participants with high working memory capacity were more sensitive to the manipulation of syntactic structure, and were more able to use animacy to parse the sentence as compared with the participants with low working memory capacity (e.g., Bornkessel et al. 2004; Domenico et al. 2010; Friederici et al. 1998; King and Kutas 1995; Long et al. 2008; Nakano et al. 2010; Traxler et al. 2005; Vos et al. 2001). Other studies found that the inability to inhibit information that is no longer relevant was correlated with poor reading skills (Carretti et al. 2005; Palladino et al. 2001). Those studies were interested in the effect of available working memory capacity, or the inhibit function of working memory, on language processing. The present study is the first to examine how individual differences in the speed of working memory updating influence the on-line interpretation of thematic roles. Generally, the present results were consistent with the previous studies by showing that individuals with quick updating ability can be more sensitive to the syntactic and animacy cues and more efficiently process

the sentences. Importantly, the present study also provided new insights to our understanding of the relationship between working memory and sentence comprehension. First, previous studies on working memory and language processing just focused on one source of information types. The present study examined both the use of syntactic information and the use of animacy information during on-line sentence processing. We found that only individuals with quick updating ability can combine the multiple sources of information (e.g., both animacy information and syntactic information) and individuals with slow updating ability only rely on one dominant source of information types (e.g., word order). Secondly, as mentioned in the introduction section, the working memory theory put forward by Lewis and colleagues (Lewis and Vasishth 2005; Lewis et al. 2006) emphasizes a sharply attentional focus in sentence comprehension and carves up working memory processes into stages of encoding, storage, and retrieval. The present study, for the first time, revealed that how the individual differences in the speed of working memory updating influence the whole time course of thematic processing (e.g., argument encoding, storage, retrieval and integration with the following verb). Our results indicated that, relative to the slow-updating individuals, the quick-updating individuals not only can allocate more resources to maintain the important initial argument when new information arrives, but also can more rapidly and efficiently integrate that argument with the disambiguating verb at a later time point. Specifically, when integrating the initial argument with the following verb, the quick-updating group can conduct rapid and fine-grained two-stage analysis (computing and re-computing); the slow-updating group, however, only performed slow and course-grained analysis. The present results on the effect of working memory updating speed is interesting because this is observed during the on-line thematic processing of simple active sentence that does not involve complex syntactic structure. This shed new lights on our understanding of how working memory may influence language comprehension.

How to link the individual differences in working memory updating to the model of argument interpretation? As mentioned in the introduction section, the eADM has been put forward to explain the process of argument interpretation. According to the eADM, the thematic role of sentence arguments is assigned in two phases: at the early stage of compute prominence and compute linking (usually within the window latency of N400 component), the noun argument is linked to the verb's lexical entry by referring to morphosyntactic and prominence cues; at the later stage of generalized mapping (usually within the window latency of P600 component), other interpretively relevant information types are also taken into account in

order to construct a full argument interpretation (Bornkessel and Schlesewsky 2006; Bornkessel-Schlesewsky and Schlesewsky 2008, 2009a, Bornkessel-Schlesewsky et al. 2009b). Moreover, based on available cross-linguistic facts, the word order effect (namely, subject-preference) has been attributable to an epiphenomenon of minimal events, which leads to an initial ambiguous argument being interpreted as the sole argument in the sentence (thereby, sole argument $\pm$ intransitive verb) (e.g., Demiral et al. 2008; Wang et al. 2009; Wolff et al. 2007). From this perspective, it might be that the initial ambiguous argument was analyzed as the sole argument of an intransitive verb. On the one hand, for the quick-updating group, when the disambiguating transitive verb was subsequently reached, they could, at the early processing stage, quickly update the interpretation based on minimal events. The updating from the sole argument reading to a patient-first reading is more costly than the updating to an agent-first reading. Therefore, at the early processing stage, the quick-updating group demonstrated a subject-preference effect, which was more pronounced in the harder inanimate conditions as discussed in the early part of the discussion section. At the later processing stage, the quick-updating group can quickly take into account all kinds of information (including additional interpretively relevant information types) to re-compute the thematic roles and to override the early-stage processing results, resulting in a pattern of fine-grained two-stage processing. On the other hand, for the slow-updating group, at the early processing stage, neither the word order cue nor the animacy cue was used to compute the thematic roles, which might be due to the slow processing speed of this group; meanwhile, at the later processing stage, this slow group only relied on one dominant source of information, word order, to evaluate the well-formedness of the initial argument interpretation, resulting a subject-preference effect. The relationship between individual difference and the updating process in sentence comprehension observed in the present study was in line with an early ERP study. This early ERP study examined the telicity effect on on-line syntactic reanalysis of object reduced relative clauses with normal and high-normal syntactic proficiency. The participants were asked to read sentences in which the main verb was either telic or atelic, e.g., “The actress awakened/worshipped by the writer left in a hurry”. The results demonstrated that the ERP waveform elicited by the atelic condition was more negative than that elicited by the telic conditions, which might be due to the fact that the atelic condition need reanalysis of argument roles, while, the telic condition doesn’t; more importantly, this telicity effect started earlier in the high-normal group (from the second argument) as compared with the normal group (from the word “by”) (Malaia et al. 2009). Overall, both the present study and

Malaia and colleagues’ study indicated that, during sentence comprehension, the syntactic and semantic information available with the verb controls the initial stages of comprehension, which can be quickly modified or updated by the information coming later; moreover, individual differences in working memory updating or processing proficiency can influence the speed or the ability of that updating process in sentence comprehension. In short, this study just tries to explain the effect of working memory updating on sentence processing within the framework of language comprehension models. In future, more cross-linguistic research is needed to link the speed of working memory updating to the language comprehension process or other cognitive processes.

Acknowledgments This research was supported by Grants from the National Natural Science Foundation of China (31271091).

Appendix: parts of the experimental sentences (just including the main structure of the sentence, namely “Noun + Verb + ‘le’ + a two-character word”)

Animate

1. Agent-first	蜘蛛/编织/了/丝网	Spider/weave/‘le’/web The spider has woven a web
Patient-first	蜘蛛/晒死/了/几只	Spider/dry dead/‘le’/several Several spiders have been dried dead
2. Agent-first	兔子/挖好/了/洞穴	Rabbit/dig/‘le’/cave The rabbit has dug a cave
Patient-first	兔子/买来/了/一窝	Rabbit/buy/‘le’/a nest A nest of rabbits has been bought
3. Agent-first	蚊子/叮咬/了/表弟	Mosquito/bite/‘le’/cousin The mosquito has bitten my cousin
Patient-first	蚊子/消灭/了/一群	Mosquito/eliminate/‘le’/a group A group of mosquitoes has been eliminated
4. Agent-first	水母/蜇到/了/游客	Jellyfish/sting/‘le’/visitor The jellyfish has stung the visitor
Patient-first	水母/捞出/了/一只	Jellyfish/take out of the water/‘le’/one One jellyfish has been taken out of the water
5. Agent-first	囚徒/供认/了/罪行	Prisoner/admit/‘le’/crime The prisoner has admitted his crime
Patient-first	囚徒/押送/了/一车	Prisoner/send under guard/‘le’/a cart A cart of prisoners been sent under guard

continued

6. Agent-first	狮子/啃断/ 了/栏杆	Lion/gnaw off/‘le’/handrail The lion has gnawed off the handrail
Patient-first	狮子/救活/ 了/一头	Lion/save/‘le’/one One lion has been saved
7. Agent-first	保姆/打扫/ 了/地板	Nursemaid/clean/‘le’/floor The nursemaid has cleaned the floor
Patient-first	保姆/辞退/ 了/一个	Nursemaid/discharge/‘le’/one One nursemaid has been discharged
8. Agent-first	小鸡/啄食/ 了/小米	Chick/eat/‘le’/millet The chick has eaten the millets
Patient-first	小鸡/喂养/ 了/一批	Chick/feed/‘le’/a group A group of chicks has been fed
9. Agent-first	大象/卷起/ 了/木桩	Elephant/roll up/‘le’/timber pile The elephant has rolled up the timber pile
Patient-first	大象/驯化/ 了/三只	Elephant/domesticate/‘le’/three Three elephants have been domesticated
10. Agent-first	白鼠/啃咬/ 了/沙发	The white rat/bite/‘le’/sofa The white rat has bitten the sofa
Patient-first	白鼠/解剖/ 了/几只	The white rat/dissect/‘le’/a few A few white rats have been dissected
11. Agent-first	罪犯/劫持/ 了/人质	Criminal/hijack/‘le’/hostage The criminal has hijacked the hostage
Patient-first	罪犯/逮捕/ 了/几个	Criminal/arrest/‘le’/several Several criminals have been arrested
12. Agent-first	小猫/舔光/ 了/牛奶	Cat/lick up/‘le’/milk The cat has licked up the milk
Patient-first	小猫/抱来/ 了/两只	Cat/carry here in one’s arms/‘le’/two Two cats have been carried here in his arms
13. Agent-first	蚂蚁/搬来/ 了/食物	Ant/convey here/‘le’/food The ants have conveyed here some food
Patient-first	蚂蚁/碾死/ 了/许多	Ant/crush to death/‘le’/some Some ants have been crushed to death
14. Agent-first	海豚/托顶/ 了/水球	Dolphin/hold up/‘le’/water ball The dolphin has held up the water ball
Patient-first	海豚/猎杀/ 了/一只	Dolphin/hunt/‘le’/one One dolphin has been hunted
15. Agent-first	患者/服下/ 了/药丸	Patient/take/‘le’/pill The patient has taken the pill
Patient-first	患者/治愈/ 了/两个	Patient/cure/‘le’/two Two patients have been cured

continued

16. Agent-first	苍蝇/传播/ 了/细菌	Fly/disseminate/‘le’/bacteria The flies have disseminated the bacteria
Patient-first	苍蝇/拍扁/ 了/两只	Fly/flat/‘le’/two Two flies have been flattened
17. Agent-first	鲤鱼/挣开/ 了/渔网	Carp/break/‘le’/fishing net The carp has broken the fishing net
Patient-first	鲤鱼/网到/ 了/两条	Carp/net/‘le’/two Two carps have been netted
18. Agent-first	幼童/摔坏/ 了/玩具	Child/destroy by beating/‘le’/toy The child has destroyed the toy by <u>beating</u>
Patient-first	幼童/看护/ 了/一会	Child/look after/‘le’/a while The child has been looked after for a while
19. Agent-first	母猪/拱翻/ 了/围墙	Sow/knock over/‘le’/wall The sow has <u>knocked over</u> the wall
Patient-first	母猪/卖掉/ 了/几只	Sow/sell/‘le’/several Several sows have been sold
20. Agent-first	乌鸦/啄伤/ 了/小鸟	Crow/peck/‘le’/little bird The crow has pecked the little bird
Patient-first	乌鸦/煮熟/ 了/一只	Crow/cook/‘le’/one One crow has been cooked
21. Agent-first	黄蜂/攻击/ 了/农夫	Wasp/attack/‘le’/farmer The wasps have attacked the farmer
Patient-first	黄蜂/灭杀/ 了/一群	Wasp/kill/‘le’/a group A group of wasps has been killed
22. Agent-first	盗贼/抢劫/ 了/银行	Thieves/loot/‘le’/bank The thieves have looted the bank
Patient-first	盗贼/审判/ 了/四个	Thieves/bring to trial/‘le’/four Four thieves have been brought to trial
23. Agent-first	蚂蚱/破坏/ 了/庄家	Locust/damage/‘le’/crops The locusts have damaged the crops
Patient-first	蚂蚱/扣到/ 了/一只	Locust/ cover with an inverted cup/ ‘le’/one One locust has been covered with an inverted cup
24. Agent-first	龙虾/抖掉/ 了/水珠	Lobster/shake off/‘le’/droplet The lobster has shaken off the droplets
Patient-first	龙虾/放生/ 了/几只	Lobster/free/‘le’/several Several lobsters have been freed
25. Agent-first	熊猫/摘光/ 了/竹叶	Pander/pick/‘le’/bamboo leaves The panders have picked all of the bamboo leaves
Patient-first	熊猫/运来/ 了/两只	Hot-water/transport here/‘le’/two Two panders have been transported here

Inanimate

1. Agent-first	寓言/教育/ 了/大家	Fable/educated/'le'/everyone The fable has educated everyone
Patient-first	寓言/讲述/ 了/一遍	Fable/tell/'le'/once The fable has been told once
2. Agent-first	大雪/冻坏/ 了/桃花	Snow/freeze/'le'/peach flower The snow has frozen the peach flower
Patient-first	大雪/清扫/ 了/半天	Snow/clean/'le'/long time The snow has been cleaned for a long time.
3. Agent-first	毒品/伤害/ 了/身体	Drug/hurt/'le'/body The drug has hurt someone's body
Patient-first	毒品/销毁/ 了/一些	Drug/destroy by burning/'le'/some Some drugs have been destroyed by burning
4. Agent-first	琴盖/砸伤/ 了/小狗	Piano lid/injure by a crashing object / 'le'/dog The piano lid has injured the dog
Patient-first	琴盖/卸下/ 了/一个	Piano lid/dismantle/'le'/one One piano lid has been dismantled
5. Agent-first	海报/占满/ 了/地铁	Poster/occupy/'le'/subway The posters have occupied the subway
Patient-first	海报/贴出/ 了/十张	Poster/put up/'le'/ten Ten posters have been put up
6. Agent-first	纱布/止住/ 了/鲜血	Gauze/stop/'le'/blood The gauze has stopped the blood
Patient-first	纱布/夹起/ 了/一块	Gauze/pick up/'le'/one piece of One piece of gauze has been picked up
7. Agent-first	诗歌/感动/ 了/听者	Poem/move/'le'/audience The poem has moved the audience
Patient-first	诗歌/朗诵/ 了/一遍	Poem/read aloud with expression/ 'le'/once The poem has been read aloud with expression once
8. Agent-first	玉镯/迷住/ 了/阿姨	Jade bracelet/fascinate/'le'/aunt The jade bracelet has fascinated my aunt
Patient-first	玉镯/拧坏/ 了/一个	Jade bracelet/damage by screwing/ 'le'/one One jade bracelet has been damaged by screwing
9. Agent-first	镜子/反射/ 了/灯光	The mirror/reflect/'le'/light The mirror has reflected the light
Patient-first	镜子/打破/ 了/一面	The mirror/break/'le'/one One mirror has been broken
10. Agent-first	管道/输送/ 了/凉水	Pipeline/deliver/'le'/water The pipeline has delivered the water
Patient-first	管道/打通/ 了/两条	Pipeline/open up/'le'/two Two pipelines have been opened up

Table b continued

11. Agent-first	堤坝/拦住/ 了/洪流	Dam/stop/'le'/flood The dam has stopped the flood
Patient-first	堤坝/冲垮/ 了/一半	Dam/damage by the thunderstorm/ 'le'/half Half of the dam has been damaged by the thunderstorm
12. Agent-first	雨伞/挡住/ 了/阳光	Umbrella/block/'le'/sun The umbrella has blocked the sun
Patient-first	雨伞/撑开/ 了/一把	Umbrella/open/'le'/one One umbrella has been opened.
13. Agent-first	墨镜/吓哭/ 了/女孩	Sunglasses/scared to tears/'le'/girl The sunglasses have scared the girl to tears
Patient-first	墨镜/丢掉/ 了/一副	Sunglasses/throw away/'le'/one pair One pair of sunglasses has been thrown away
14. Agent-first	烟尘/迷伤/ 了/眼睛	Smoke/confuse/'le'/eyes The smoke has confused his eyes
Patient-first	烟尘/吹散/ 了/一些	Smoke/blow away/'le'/some Some smokes have been blown away
15. Agent-first	雨水/滋润/ 了/树苗	Rainwater/moisten/'le'/saplings The rainwater has moistened the saplings
Patient-first	雨水/收集/ 了/一些	Rainwater/save/'le'/some Some rainwater has been saved
16. Agent-first	墙纸/遮住/ 了/裂痕	Wallpaper/cover/'le'/crack The wallpaper has covered the crack.
Patient-first	墙纸/绘制/ 了/一面	Wallpaper/draw/'le'/one piece One piece of wallpaper has been drawn
17. Agent-first	豆油/弄湿/ 了/灶台	Soya-bean oil/wet/'le'/the top of kitchen range The soya-bean oil has wetted the top of kitchen range
Patient-first	豆油/倒掉/ 了/两桶	Soya-bean oil/pour out/'le'/two barrels Two barrels of soya-bean oil have been poured out
18. Agent-first	糖块/腐蚀/ 了/牙齿	Sugar/corrode/'le'/teeth The sugar has corroded the teeth
Patient-first	糖块/研制/ 了/几种	Sugar/invent/'le'/several kinds Several kinds of sugar have been invented
19. Agent-first	瓶盖/封住/ 了/水壶	Bottle cap/seal/'le'/kettle The bottle cap has sealed the kettle
Patient-first	瓶盖/拧开/ 了/一个	Bottle cap/twist off/'le'/one One bottle cap has been twisted off
20. Agent-first	指甲/划开/ 了/手臂	Fingernail/gash/'le'/arm The fingernail has gashed his arm

Table b continued

Patient-first	指甲/剪掉/ 了/几片	Fingernail/cut off/'le'/several pieces Several pieces of fingernails have been cut off
21. Agent-first	墨水/浸透/ 了/纸张	Ink/soak/'le'/paper The ink has soaked the paper
Patient-first	墨水/挤出/ 了/一些	Ink/squeeze out/'le'/some Some ink has been squeezed out
22. Agent-first	小刀/切开/ 了/木头	Knife/cut apart/'le'/wood The knife has cut apart the wood
Patient-first	小刀/掰断/ 了/一个	Knife/break off with hands/'le'/one One knife has been broken off with hands
23. Agent-first	奶酥/诱来/ 了/老鼠	Butter biscuit/lure here/'le'/mouse The butter biscuit has lured here the mouse
Patient-first	奶酥/分发/ 了/一些	Butter biscuit/hand out/'le'/some Some butter biscuits have been handed out
24. Agent-first	染料/漂染/ 了/衣服	Dyestuff/dye/'le'/clothes The dyestuff has dyed the clothes
Patient-first	染料/挑选/ 了/一瓶	Dyestuff/select/'le'/one bottle One bottle of dyestuff has been selected
25. Agent-first	香水/取悦/ 了/女孩	Perfume/please/'le'/girl The perfume has pleased the girl
Patient-first	香水/调配/ 了/一瓶	Perfume/blend/'le'/one bottle One bottle of perfume has been blended

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