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The Impact of Bilingualism on Storage and Processing in Working Memory

An experimental dual-task study

Abstract: Working memory as a cognitive system refers to a mental workspace involved in the temporary storage and processing of information. Although many scholars have looked extensively at the implications of WM for second language acquisition or for translation, the inner relationship of WM is still underdeveloped. The purpose of this study is to investigate 1) whether the interaction between storage and processing-based functions of verbal working memory is positive or negative, 2) and whether the interaction between working memory capacity and language proficiency is language-specific. Thirty-three students were allowed to participate in the experiments. Both the processing and storage functions of verbal WM in language contrasts (L1/L2) were separately assessed via a dual-task paradigm programmed in the E-Prime. The correlation coefficient indicates two relationships within bilingual WM capacity: 1) between L1 WM storage and L1 WM processing; 2) between L2 WM storage and L2 WM processing. These results demonstrate that verbal WM capacity is language-dependent and that there is a positive correlation between WM storage and WM processing.

Keywords: dual-task paradigm; verbal working memory; storage and processing, language-dependent effect, cognitive linguistics

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1 Research questions

Working memory (WM) as a cognitive system (Baddeley and Hitch 1974) refers to a mental workspace which has two separate systems, a storage-based system, analogous to short-term memory (STM), and an executive system that controls the flow of information between the short-term storage systems and long-term memory

(Baddeley 1986; Baddeley and Hitch 1974; Cowan 1998; Juffs and Harrington 2011).

1.1 Relationship between storage and processing: Decay or interference?

Since Baddeley's theoretical model, experts generally agree that "WM is a multi-component system responsible for active maintenance of information in the face of ongoing processing and/or distraction" (Conway et al. 2005: 770). Although many scholars have looked extensively at the implications of WM for second language (L2) acquisition (e.g. Michael and Gollan 2005; Tokowicz et al. 2004; Linck and Weiss 2011; Martin and Ellis 2012; Robinson 2001, 2002; Skehan 2002) and for translation (e.g. Darò and Fabbro 1994; Mizuno 2005; Zhang 2011; Cai 2001), the inner relationship between the processing and storage functions of WM is still underdeveloped. Four main explanations of this relationship have been proposed (cf. Miyake 2001; Oberauer 2009; Sun et al. 2012): 1) the resource-sharing account (Daneman and Carpenter 1980; Just and Carpenter 1992; Case et al. 1982) suggests that WM is a limited-capacity system in which resources are consumed by both processing and storage components, leading to a trade-off hypothesis of resource availability within the subsystems; 2) the task-switching hypothesis (Hitch et al. 2001) assumes that WM performance may suffer from the overlapping task execution, i.e., WM capacity is not only associated with trade-offs between storage and processing but also with difficulty in switching from storage to processing, and vice versa; 3) the time-based resource-sharing model (or decay-based model) (Barrouillet et al. 2004; Towse et al. 2000) assumes that the sharing of attention functions through a process of rapid switching of focus between processing and storage, and, in addition, the processing task delays recall while preventing rehearsal, so that memory traces decay over time; 4) the interference-based model (Saito and Miyake 2004; Oberauer and Lewandowsky 2008) finds that only the amount of material affects memory and assumes that there is interference between memory items and representations involved in the processing task.

1.2 Working memory capacity: Language independent or language specific?

In the past four decades, psycholinguistics and cognitive linguistics have focused on verbal WM in bilingual speakers. A number of L2 theoretical and empirical studies support the language specificity of verbal WM because of the differences in language structure, for example in grammar, morphology, and syntax (e.g. van den

Noor et al. 2006; Marton and Schwartz 2003; Marton et al. 2006). While others propose that verbal WM is immune to language differences (Harrington and Swayer 1992; Miyake and Friman 1998; Osaka et al. 1993; Swanson et al. 2004), Harrington and Swayer (1992) test the performance of WM in English and Japanese, and their findings suggest that the capacity of verbal WM in the mother tongue (L1) is related to the capacity in L2. The study from Alptekin and Ercetin (2010) places even greater emphasis on the correlation between WM storage and WM processing for both L1 (Turkish) and L2 (English). The latest findings (L1 Chinese; L2 English) from Sun et al. (2012) support that WM processing is cross-linguistic, whereas the WM storage is language specific; and according to the meta-analysis from John N. Williams (2012: 428), "WM is a multi-component system comprising domain-specific storage systems and a domain-general executive component"; the study from Wei et al. (2014) concludes that the static structure of bilingual working memory contains both shared features and distinct features, and that, with the development of L2 proficiency, the L2 processing rate speeds up while the impact of the processing rate on overall L2 proficiency decreases. Meanwhile, the impact of storage capacity on L2 proficiency increases and finally surpasses the impact of processing rate and becomes the most important factor influencing L2 proficiency.

Given the above considerations, the research questions for this empirical study are: 1) whether the dynamic relationship between storage and processing-based functions of verbal working memory supports the decay-based model or the interference-based model; and 2) whether the interaction between working memory capacity and language proficiency is language-specific.

2 Research method and materials

2.1 Participants

We chose thirty-five MTI[1] student translators from nine Chinese universities in their second or third year to complete two online selective entry tests, including an IQ test and a personal information questionnaire (about age, foreign language proficiency, handedness, vision, etc.) to keep the controlled variables consistent. According to the tests results, thirty-three of them were allowed to participate in the study (concerning the other two: one was left-handed, and another had a lower level in German, the L2), including thirty-one girls and two boys with an average

[1] MTI = Master of Translation and Interpretation

age of 24 years. All of them were right-handed, native Chinese-speakers whose major was German, and none had spent more than 1 year in German-speaking countries. Moreover, they did not know the purpose of the experiment until the end of the experiment.

2.2 Research method

Both the processing and storage functions of verbal WM in language contrasts (L1/L2) were separately assessed via a set of tests based on a verbal and visual dual-task paradigm (Shah and Miyake 1996; Bayliss et al. 2003; Sun et al. 2012; Unsworth et al. 2009), programmed using the E-Prime software, whereas the verbal WM capacity was measured via the retention interval of a visuospatial WM task. We conducted two experiments in which participants were asked to perform two tasks simultaneously. That means that the participants received both a verbal and a visual stimulus in the same trial.

Experiment I (verbal WM storage span testing) consisted of a visuospatial reasoning task, which required the participants to answer whether various graphics were symmetrical or asymmertrical, and a verbal span task, which required them to recall a list of Chinese characters (in the L1 version) or German words (in the L2 version).

Experiment II (verbal WM processing span testing) consisted of a visuospatial span task, which required the participants to recall the spatial positions of a set of graphics, and a verbal reasoning task, which required them to answer whether various Chinese sentences (in L1 version) or German sentences (in L2 version) were grammatically correct.

Overall, we provided four sets of tests. Each set was a distinct combination of language (L1/L2) and function (storage/processing).

For each span task, firstly, we gave the instruction information to the participants, which explained how the present experiment would proceed and how to respond. Also, we built in an example exercise containing two blocks which participants could practice repeatedly until they were familiar with the experimental procedure (see Figure 1). The core experimental procedure (CEP) contains a certain number of blocks (n) with the nth block containing n+1 trials. For example, there are five trials in the 4th block.

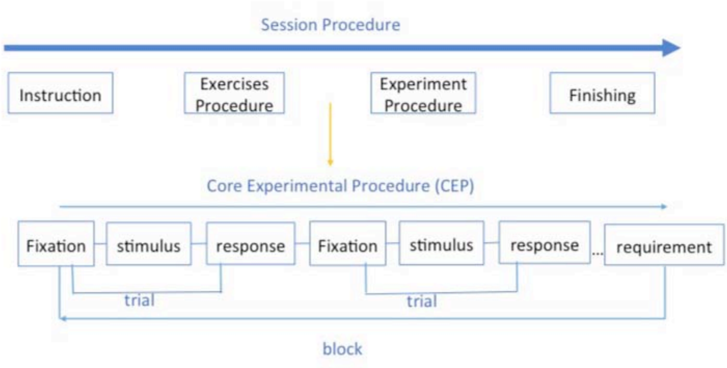

Figure 1: An overall scheme of the experimental process

2.3 Pre-experiment

In order to provide an efficient evaluation of bilingual working memory and avoid cognitive overload, we chose ten MTI students with very similar qualifications to the regular participants. According to their subsequent performance, we found the appropriate number of blocks for verbal WM Span for storage and processing components. After adjustment, there were six blocks in the WM storage span task and four blocks in the WM processing span task (see Table 1). Also, we adjusted both the quantity and difficulty of the experimental materials to make them suitable for the participants. The details of the verbal materials and graphics are shown in the following chapter.

Table 1: Adjustment for experiment blocks

	Span task for WM storage		**Span task for WM processing**	
	pre-experiment	experiment	pre-experiment	experiment
Blocks	8	6	6	4
Trials	2–9	2–7	2–7	2–5

2.4 Experimental materials

We chose parallel verbal materials in L1 and L2, taking care to keep the linguistic difficulty at the same level. For the WM storage span task, all twenty-seven Chinese characters came from the HSK[2] Grade 3 vocabulary, and the twenty-seven German words were chosen from the PGG[3] vocabulary with two syllables. Both the characters and the words were normal vocabulary used in daily life. That way, we could ensure that all the participants were familiar with the words. Language proficiency could be controlled by testing their memory span.

Table 2: Verbal materials for WM span in L1 and L2

	Span task for WM storage		**Span task for WM processing**	
	Chinese characters	German words	Chinese sentences	German sentences
Number	27	27	14	14
Standards	HSK Graded 3 normal vocabulary	PGG normal vocabulary with two syllables	17-19 characters High-School	17-19 words PGG

Moreover, for the graphical materials of the WM storage span task, we ensured that the proportion of symmetrical to asymmetrical pictures was almost 1:1 in order to avoid the effects of congruence bias[4]. In addition, we prepared sixteen images of a 4×4 grid of squares, in which one square would randomly be colored red (but never the same square consecutively).

Table 3: Graphical materials for WM span in L1 and L2

	Span task for WM storage function		**Span task for WM processing function**
L1 version	asymmetric (14)	symmetric (13)	4×4 grid of squares (16)
L2 version	asymmetric (14)	symmetric (13)	4×4 grid of squares (16)

2 HSK = Chinese Proficiency Test.
3 PGG = Prüfung für das Germanistik-Grundstudium.
4 Congruence bias is a type of cognitive bias similar to confirmation bias. It occurs due to people's overreliance on directly testing a given hypothesis as well as neglecting indirect testing.

3 Experiment I: WM storage task in L1 and L2

The span task for the storage component of verbal WM consists of two sets of tests. The first set is in the L1 version and the second set in the L2 version. After reading the instructions and practicing, participants were shown a series of trials. Each trial circuit proceeded as follows:

(1) A red cross (0.4° visual angle) appeared as a fixation point in the center of the screen for 1300 msec;

(2) One of the twenty-seven words (in the L1 version: a Chinese character; in the L2 version: a German word) appeared randomly in the center of the screen for 1800 msec. The task for participants here was to read aloud the presented Chinese or German word and remember it;

(3) One of the twenty-seven graphics appeared randomly in the center of the screen (Duration: infinite). The participant needed to judge as soon as possible whether each presented picture was symmetrical (by pressing the Button “J”) or asymmetrical (by pressing the Button “F”). The picture faded, until the participant responded by pressing the corresponding button on the keyboard. During this stimulus, there was a 200 msec musical tone as interference (Buffer Mode: repeated until response).

In the experimental procedure, there were six blocks, each of which contained two to seven trials. At the end of each block, participants were shown a recall-task screen and required to recall all the words or characters within this circuit in order. The participants needed to finish the (at most) seven visual-judgment and verbal-recall tasks at one time, namely in the 6th block. We checked and graded the correctness of the participant’s verbal recall performance. If the answer was correct, we then ask the participant to press the Button “P” to continue to the next block; if not, then the participant needed to press the Button “Q” to terminate the task.

4 Experiment II: WM processing task in L1 and L2

In this experiment, participants also needed to complete two sets of the same test, one in each language (L1 and L2). It also began with reading instructions and doing some practice. Then participants were led through the experimental procedure. In both the L1 version and the L2 version, there were four blocks, and two to five trials. Each trial proceeded as follows:

(1) A red cross appeared as a fixation point in the center of the screen for 1300 msec, to draw the attention of the participant;
(2) One of the fourteen sentences in each version appeared randomly on the screen. Participants needed to judge as soon as possible whether the presented sentence was grammatically correct (by pressing the Button “J”) or incorrect (by pressing the Button “F”). The presentation ended when the participant responded using the keyboard.
(3) Then, the participants saw one of fourteen images of a 4×4 grid of squares, which appeared in the center of the screen for 2300 msec; in each picture one square was colored red (but never the same square consecutively). The task here was to recall the positions of the red squares.

At the end of each block, participants were shown a test paper with a 4×4 grid of squares; they needed to mark all the positions of the presented red squares in this circuit, which means, the participants needed to recall at most five spatial positions at one time, namely in the fourth block.

5 Results

5.1 WM storage capacity in L1 and L2

In experiment I, we manually recorded whether the participants correctly recalled the presented words, whereas the response time and correctness of the visual judgment performance was automatically recorded by *E-prime*.

According to the data for visual judgment performance both in L1 and L2 (see Table 2.), we found that the participants did pay attention to the visual judgment task rather than only concentrating on the verbal memory task. So, the separate results for the verbal memory task in two languages can be confirmed as effective.

Table 4: Visual judgment performance in L1 and L2

	Visual judgment performance in L1		**Visual judgment performance in L2**	
	response time (msec)	correct	response time (msec)	correct
Mean	1405.394	0.833	1561.862	0.774
SD	433.037	0.103	444.771	0.119

Then, we calculated the correctness of the verbal-recall task to get the specific WM storage span of the participants. The formula is as follows, which was used in both tests in L1 and L2:

$$\text{storage span of verbal WM} = (n + 1) - a \times \frac{1}{(n + 1)}$$

Here "n" represents the block series, "n+1" means the latest trial in this block, and "a" represents the error counters (including recall mistakes and unrecallable items) in this trial. The marking scale here is a 7-point grading scale. For example, if a participant in the fourth block (e.g. in the L1 version) correctly recalls three Chinese characters (e.g. in the L1 version), forgets one character, and makes one mistake for recalling, then his span for WM storage span in L1 equals 4.6 points (5-2×(1/5)).

Table 5: Verbal recall performance in L1 and L2

	Verbal recall performance in L1	**Verbal recall performance in L2**
Mean	6.462	4.173
SD	0.622	0.766

The average results of thirty-three students show that the verbal WM storage performance in L1 (6.462) is better than in L2 (4.173) and students' WM storage capacity in L1 is greater than in L2, which indicates that there is a language-specific difference in verbal WM storage performance within the participants.

5.2 WM processing capacity in L1 and L2

After experiment II, we collected the test paper in order to check whether the participant correctly recalled the spatial positions of the squares. If the participant was correct less than 30% of the time, we believe that his/her attentional resources did not switch across the dual tasks, which means that he/she only paid attention to the verbal judgment task, which would have gone against the meaning of dual-task paradigm, and his/her data would have needed to be excluded. However, all of the thirty-three participants passed; all their scores for the spatial positions recall task were above 30% (the lowest score among them was 35.71%).

Table 6: Spatial positions recall performance in L1 and L2

	Spatial positions recall performance in L1	**Spatial positions recall performance in L2**
Correct answer counters	10.485 (14)	10.606 (14)
Accuracy	0.749	0.758

In this experiment, the response time and correctness for the sentence judgment task was automatically recorded with the help of E-prime. Then, we calculated the standard score (or Z-score) to assess the verbal processing performance in L1 and L2. “$\bar{X}$” is the mean and “S” is the standard deviation of the sample. If a Z-score is negative, this means that the performance is below average, if positive then above average. In our case, the Z-score of the thirty-three participants needed to be separately calculated for four metrics, i.e. for response-time and response accuracy in L1/L2 verbal WM processing performance.

$$Z = \frac{X - \acute{X}}{S}$$

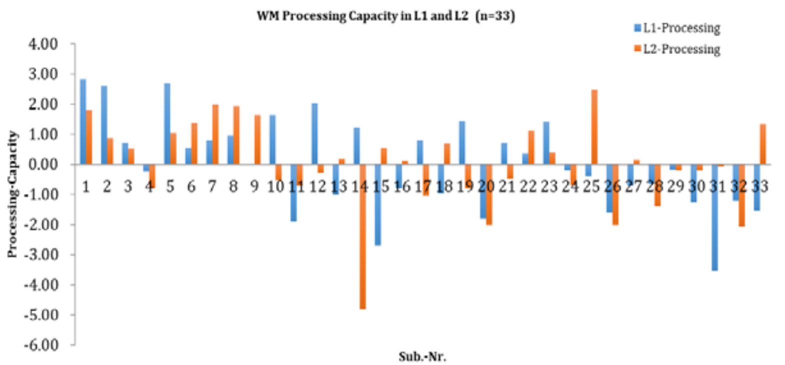

Figure 2: Verbal WM processing performance in L1 and L2 based on processing accuracy ($Z_{\text{-a.}}$) and reaction time ($Z_{\text{-r.t.}}$) provided the combined z-score ($Z_{\text{-t.}}$) for verbal WM processing performance in L1 and L2, which was

$$Z_{t.} = Z_{a.} - Z_{r.t.}$$

In our case, for example, the first participant took on average 4872.64 msec to judge one sentence, and she judged twelve of 14 sentences correctly in the L1 version. Her Z-score for response time ($Z_{\text{-r.t.}}$) was -0.73 (=(4872.64-

6099.20)/1689.30), and response accuracy ($Z_{-a.}$) was 2.08 (=(0.86-0.63)/0.11). According to her behavior data (incl. response time and accuracy), she obtained a score of 2.81 points (=2.08-(-0.73)) for her total performance of verbal WM processing performance in L1.

In this way, we calculated all the scores for the verbal WM storage performance in L1 and L2 for the thirty-three participants. From the tendency chart (see Figure 2), we suggest that verbal WM storage performance is not immune to language differences but is language dependent.

5.3 Correlation analysis

After collecting all the behavior data from the four tests from the thirty-three participants, we performed a correlation analysis in *SPSS Statistics*. The Pearson coefficient of correlation "r" will show us the strength and the direction of a linear relationship between two variables. According to the p-value (or probability value), we find that there are two significant relationships within monolingual WM capacity: 1) between L1 WM storage and L1 WM processing (r=0.355, significant); and 2) between L2 WM storage and L2 WM processing (r=0.377, significant).

Table 7: Correlations between WM storage and WM processing (n=33). * means: p <.05 (2-tailed), significant.

		M	**SD**	**1**	**2**	**3**
1	L1 WM storage	6.46	.62	—		
2	L2 WM storage	4.13	.76	.291	—	
3	L1 WM processing	.00	1.54	.355*	.145	—
4	L2 WM processing	.00	1.47	.257	.377*	.176

However, there are no significant bilingual relationships between L1 WM storage and L2 WM storage (r=0.291, insignificant) or L1 WM storage and L2 WM processing (r=0.176, insignificant).

These results demonstrate that verbal WM capacity is not immune to language differences but is language dependent. As for the internal relationship within one language, for both L1 and L2, namely, there is a positive correlation between WM storage and WM processing.

6 Discussion and conclusion

As mentioned above, we draw the following two conclusions:

First, verbal WM capacities have cultural-linguistic differences. We cannot use verbal WM capacity in one language to represent or predict the capacity in another language. It should be tested separately. Our empirical evidence supports the language specificity of verbal WM. German and Chinese have two different affiliations, one is in the Indo-European language family and the other in the Sino-Tibetan language family, and the differences of language structures influence their verbal WM.

Second, there is a positive correlation between the storage component and processing component of verbal WM within each language, but not between languages. The correlation analysis confirms this conclusion for both L1 and L2. Moreover, the result also supports a multi-component structure of verbal working memory. It also demonstrates that its storage span can significantly account for the processing performance, instead of interference.

Distinguishing WM capacities from cultural-linguistic and multi-component differences is a key issue for many language educators, linguists, and translators. It provides a new way of thinking about and a method for the practice of the teaching of foreign languages, translation, and interpretation. We suggest that foreign language majors give students some additional verbal working memory training for both languages, L1 and L2. This would promote the students' language skills in turn. However, our conclusions extend only to bilingual WM (Chinese–German), and further studies in multilingual contexts, such as Chinese–German–English are also required.

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Bionote

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