

Updating verbal and visuospatial working memory: Are the processes parallel?

YUE ZhenZhu^{1,2}, ZHANG Ming^{3,4†} & ZHOU XiaoLin¹

¹ Department of Psychology, Peking University, Beijing 100871, China;

² Biological Psychology and Neuropsychology, University of Hamburg, Von-Melle-Park 11, 20146 Hamburg, Germany;

³ Department of Psychology, Northeast Normal University, Changchun 130024, China;

⁴ Key Laboratory for Applied Statistics of MOE, Northeast Normal University, Changchun 130024, China

The current study compared the processes of updating verbal and visuospatial working memory (WM) and examined the roles of central executive and slave systems in working memory updating tasks, by changing the number of items updated simultaneously to manipulate the load on central executive. Experiment 1 used the verbal WM updating task, and the results validated the efficiency of the paradigm to manipulate the load on central executive. Experiment 2 employed the verbal WM updating task, with the articulatory suppression task to interfere with the phonological loop. The results supported the study by Morris and Jones, revealing that the central executive system played an important role in the updating component of verbal WM, while the phonological loop was responsible for the serial recall component. Experiment 3 employed the visuospatial WM updating task, with the spatial tapping task to interfere with the visuospatial sketchpad. The results suggested that the visuospatial sketchpad and the central executive together dealt with the updating component, while the visuospatial sketchpad was responsible for the serial recall component by itself. These results are consistent with the findings that visuospatial sketchpad has close links with central executive, while the phonological loop is separated from the central executive. It suggests that updating visuospatial and verbal WM are not two parallel processes.

memory updating, working memory, central executive, phonological loop, visuospatial sketchpad

The term working memory (WM), as defined by Baddeley^[1], refers to a brain system that provides temporary storage and manipulation of information related to the current work. It has one central system called central executive (CE) and two slave subsystems. The central executive component controls and cooperates with the other two systems to perform many higher cognitive processes: the articulatory or phonological loop, which was assumed to be responsible for the manipulation of speech-based information, and the visuospatial sketchpad, which was assumed to be responsible for setting up and manipulating the visual image. Although this basic model was proposed more than 30 years ago (Baddeley & Hitch, 1974), it holds a central place in cognitive psychology and continues to be successful in guiding and stimulating research in applied and theoretical do-

main. However, it has no mechanism to allow the phonological and visuospatial subsystem to interact. A third subcomponent has been proposed to the original model, the episodic buffer^[2,3]. It is assumed to be a limited capacity store that binds together information to form integrated episodes. Furthermore, its multi-dimensional coding awareness provides a convenient binding and retrieval process. This proposal therefore emphasizes the capacity of working memory to manipulate and create new representation, rather than simply activating old memories. This new model makes it much easier to comprehend the updating operation, because people

Received February 18, 2007; accepted May 19, 2008

doi: 10.1007/s11434-008-0299-0

†Corresponding author (email: zhangm@nenu.edu.cn)

Supported by the National Natural Science Foundation of China (Grant No. 30770717)

have to keep on changing the contents of working memory according to the newer information in the updating operation.

Updating has been testified as one of the important executive functions^[4-6]. Many brain imaging researches have found that activities in right mid-dorsal prefrontal cortex (PFC), left middle frontal regions, and right frontal pole (Brodmann areas, BA9, BA46/10) are associated with updating function^[7,8]. Moreover, the event-related potential (ERP) studies indicated that the activation of the prefrontal brain areas underlay the executive activities^[9,10]. This function is to refresh continuously the contents of working memory according to the new input. It monitors the new input, and then refreshes the contents in WM by replacing the older information with the newer relevant items. It has been widely accepted that the updating function includes three operations: discarding old items from WM; reordering the items in WM; adding new items to WM. More importantly, the updating function not only stores the task-relevant information passively, but requires active operation on the content of working memory^[11].

The updating function has been generally examined with *n*-back task^[12,13] or running memory paradigm. In the current study we used running memory paradigm, which is introduced by Pollack et al.^[14] and is used to investigate the updating function^[9-11,15,16]. Participants were presented with lists of items of an unknown length, and then were required to recall serially a specific number of recent items (Figure 1). By varying the updating times (which were influenced by the length of list), we can control the demand on central executive; by varying the number of items which are required to recall, we can control the memory load. The phonological loop system is able to store only a limited number of items, but the central executive may increase this number either by taking strategy or using other relevant information. Therefore, adopting lower memory load in the experiment can avoid the possible interference on the CE.

List of item	Updating number	Updating times	Final response
<u>HRKM</u>	1	0	HRKM
<u>HRKMQ</u>	1	1	RKMQ
<u>HRKMQS</u>	1	2	KMOS
<u>HRKMQSN</u>	1	3	MQSN

Figure 1 Running memory paradigm. The participants were required to recall the 4 last items in a stimulus list. Only if both the item itself and its location are correct, the response is labeled as a correct response.

In the past decades, researchers investigated the updating in working memory with verbal or spatial tasks. However, few of them compared the differences between the verbal and visuospatial updating process. According to the working memory model, the articulatory loop and visuospatial sketchpad were independent of each other and had distinct characteristics in many aspects, such as the nature of coding, the span, and so on. Compared with verbal working memory, visuospatial working memory was an active but poorly integrated area of research. Several behavioral and brainimaging investigations provided a lot of information about whether there were anatomical overlapping neural basis and differences between the spatial and the verbal working memory tasks. For example, Smith et al.^[17] found a clear-cut hemispheric double dissociation, with the right dorsal PFC subserving spatial and the left ventral PFC as well as left pre-motor cortex subserving active maintenance of verbal information. The left inferior parietal cortex was proposed as a neural substrate for the passive phonological short-term store. Another study used position emission tomography (PET) to investigate the cortical regions for the maintenance of spatial versus phonological information in working memory^[18]. They found that bilateral anterior and posterior intraparietal sulcus, as well as right posterior superior frontal sulcus exhibited dominance for spatial working memory. Furthermore, no region specific for phonological WM was found, although underlying stimuli processing pathways for both types of information were different. However, some studies provided strong supports for an involvement of temporal cortex and a bilateral involvement of dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex (PPC) in verbal WM^[19-21].

Since it is still controversial whether the verbal and visuospatial working memory has the same neural basis, it is interesting to testify whether the visuospatial and verbal WM updating process are parallel and the different roles of central executive and slavery systems during these two processes. Exploring the central executive is difficult because the working memory system is a highly integrated system. Thus, it is hard to separate the different subsystems. The research of Morris et al.^[11,22] enlightened us.

Using a developed visuospatial memory task that did not have a large verbal component, Morris^[22] examined the role of central executive in controlling the encoding operations of the visuospatial scratchpad. He concluded

that executive control was required at the period of encoding but not during maintenance rehearsal. Therefore, the secondary task that placed a load on the central executive only produced performance decrements during encoding. It is important to note that WM sub-systems play different roles in the different processing periods, so that the working memory system should act as an integrated system during active processing. Therefore, one strategy for examining the role of the executive is to interfere with the operation of the 'slave systems' during these dynamic phases of processing while at the same time placing a heavy load on the executive and observing the degree of interfering. However, when exploring the central executive system with updating task, most studies adopted verbal secondary tasks, such as articulatory suppression and irrelevant speech to interfere the working memory task^[11], or compared the working memory updating task with phonological short-term memory task^[9,10]. Morris and Jones^[11] predicted that if memory updating requires CE resources but not the articulatory loop, and the serial recall aspect of the task requires the articulatory loop but not the central executive, then the times of updates and the effects of secondary tasks that are known to disrupt the articulatory loop should not interact. Using articulatory suppression and irrelevant speech tasks, they found that the running memory task requires two independent mechanisms: the phonological loop and the central executive. The updating process requires central executive resources, and the serial recall component needs phonological loop. However, after they controlled the memory load and manipulated the load on CE by updating times, they found that the updating times had main effect, but not the cumulate effect (that is, the participants' performance did not decrease sharply with the increase of updating times). Thus, the load on CE in their experiments may be too low to increase the updating difficulty efficiently, which made the conclusion not convincing.

There also has been considerable speculation concerning the role of executive system in visuospatial processing. Some researches argued that executive functions were involved in encoding spatial movement sequences, and executive processes may be implicated in processing spatial sequences during encoding and possibly retrieval, but not during the maintenance phase^[23]. Neuropsychological evidence also suggests that the ventrolateral (VLPFC) and dorsolateral areas (DLPFC) of the prefrontal cortex are involved in the maintenance

and manipulation of spatial information, respectively^[5]. Fisk and Sharp^[24] investigated further the role of executive system in visuospatial memory functioning, and their results showed that the load on the executive system with concurrent random letter generation impaired the performance for the spatial task, especially the recalling of the early serial locations. However, the degree of impairment was no greater on the longer lists, in which updating functions were assumed to occur. Using random, tapping, and spatial conditions separately, they found the different condition did not interfere with the operation of the 'slave systems' and CE at the same time. Probably for the same reason that the load on central executive was not high, they did not find the updating effect in longer sequences.

The present study aimed to compare the processes of updating verbal and visuospatial working memory and to identify the roles of central executive and slavery systems in different updating tasks. Here we tried to employ a more efficient way to add the load on CE by increasing the number of items updated at one time, and then further investigated the role of CE and slavery systems in the verbal and visuospatial updating task. More specifically, instead of requiring the participants to recall serially the last six items of a sequence as some researchers did, we asked them to recall the four recent items in verbal updating task and three in visuospatial updating tasks (based on the different spans in two kinds of task and the results of our pretest). In experiment 1, we examined the efficiency of controlling the CE load with this paradigm. If updating times have cumulate effect on performance decrements with an increase in updating number, the data here could prove that the method of manipulating the load on CE was effective. In experiment 2, we followed the way of controlling load on CE from Experiment 1 and examined the function of CE and phonological loop in verbal updating. Experiment 3 was conducted to examine the role of CE and visuospatial sketchpad in spatial updating. Although recency effect in all the experiments here can cause a higher accuracy rate at latter locations in updating and recall operations, it did not have great influence upon our concerned issue. Therefore, we did not do further analysis on it.

1 Experiment 1

As working memory task is sensitive to the load on CE

and slavery systems, it is important to select a better method for manipulating the load in the tasks. In Experiment 1, we controlled the numbers of items updated at the same time to vary the load on CE. This method could be demonstrated to be effective if updating times had cumulate effect on performance decrements with an increase in updating item number.

1.1 Method

(i) Participants. Twenty undergraduate and graduate students (7 males, 13 females, 20–30 years of age, mean 24.6) from the Northeast Normal University took part in the study. All the participants were right-handed, and had normal or corrected-to-normal vision. They were paid for their participation.

(ii) Apparatus and Materials. Stimuli were presented in the center of a PIII 15" computer monitor. We used capital consonants with a height of 3 cm (2.9° of visual angle). They were chosen from the alphabet, under some restrictions, e.g. no phonological similarity. The final selected consonants were C, F, G, H, J, K, L, N, P, Q, R, S, T, V, X. For each participant, stimuli were pseudo-randomly drawn from the character set to form 111 letter sequences (15 sequences for the training block, and two formal blocks of 48 sequences). In a letter sequence, no character appeared twice and the significant brevity was avoided.

(iii) Procedure. Participants sat in a dimly lit experimental chamber, 60 cm from the screen. An initial fixation cross (1.2° × 1.2° of visual angle) was presented for 2000 ms in the center of the screen. Then one of the consonant sequences was sequentially shown. Each letter was presented for 200 ms in the center of the screen, followed by a blank screen of 800 ms. An input screen for entering the response was displayed after the last consonant of a sequence. The participants were instructed to recall the last four items presented, and typed in the input screen with a keyboard. There was no time limit for typing the response. However, the participants were instructed to respond as rapidly as possible without sacrificing the accuracy rate. The average inter-trial interval (ITI) was 1000 ms (varying randomly between 900 and 1100 ms). The length of sequences was 4 letters at least, and would change with the variation of updating times. Sequences for each condition varied equiprobably, and they were all presented in pseudo-randomized order. The order of three updating conditions was counterbalanced across participants. The participants were given

the opportunity to take a break after the completion of the first block of trials.

Figure 2 shows the examples of stimulus displays in the updating one character condition. When the updating character number was two or three at one time, two or three consonants would be presented at the same time after the fourth consonant. The participants had to update two or three items (according to their order on the screen, from left to right) in their working memory content simultaneously, and reported the four recent characters in the input screen.

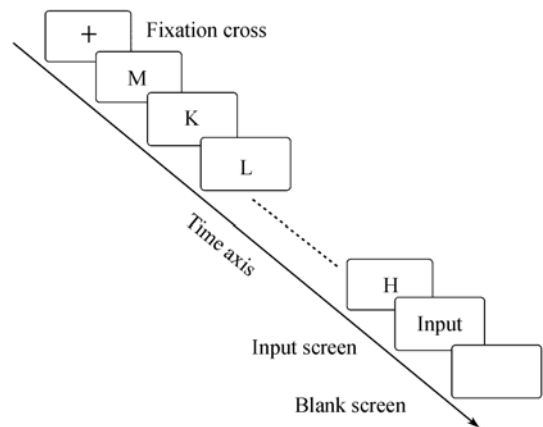


Figure 2 Examples of stimulus displays from Experiments 1 and 2.

Thus, the experiment involved a 3 × 4 × 4 within-participants design with the factors of updating number (updating character number: 1, 2, and 3), updating times (0, 1, 2, and 3), and serial location (serial location of four recent items in a sequence: 1, 2, 3, and 4).

1.2 Results

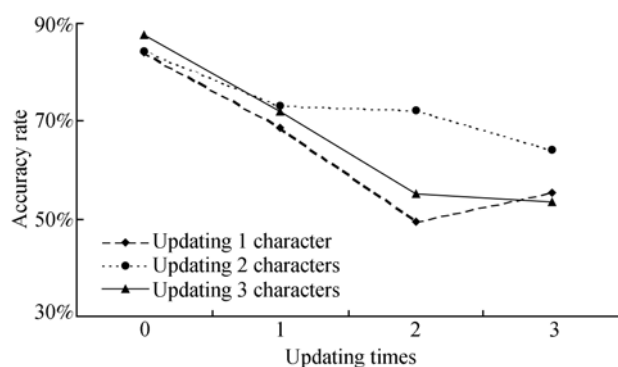
The responses for each condition were scored as accuracy rate (Table 1).

A repeated measures analysis of variance (ANOVA) was conducted on the mean accuracy rates with the variables of updating number, updating times and serial location. The three-way ANOVA revealed highly significant main effects of updating number ($F(2,38) = 5.8, P < 0.01$), updating times ($F(3,57) = 34.708, P < 0.001$), and serial location ($F(3,57) = 11.6, P < 0.001$). Both the updating number × serial location and the updating times × serial location interactions were significant ($F(6,114) = 3.1, P < 0.001$, and $F(9,171) = 2.3, P < 0.05$). The interaction between updating number, updating times, and serial location was significant ($F(18,342) = 2.3, P < 0.01$). Of more importance was that there was a significant interaction between updating number and

Table 1 The mean accuracy rates plus standard errors in different conditions of Experiment 1 (in percentage)

Update	Times	Location 1		Location 2		Location 3		Location 4	
		M	SE	M	SE	M	SE	M	SE
1 character	0	84.5	8.1	82.4	8.5	80.4	8.9	89.2	7.0
	1	65.8	10.6	67.9	10.5	65.3	10.7	75.6	9.6
	2	43.7	11.1	44.9	11.2	49.1	11.2	60.5	11.0
	3	43.6	11.1	52.4	11.2	61.3	10.9	64.5	10.7
2 characters	0	82.3	8.6	81.6	8.7	83.7	8.3	89.8	6.8
	1	67.6	10.5	74.0	9.8	72.8	10.0	78.6	9.2
	2	67.4	10.5	68.0	10.5	73.3	9.9	80.2	8.9
	3	63.2	10.8	59.1	11.0	66.7	10.6	67.3	10.5
3 characters	0	87.2	7.5	85.1	8.0	85.1	8.0	92.9	5.8
	1	69.8	10.3	79.0	9.1	69.8	10.3	69.1	10.4
	2	46.2	11.2	63.9	10.8	53.2	11.2	57.0	11.1
	3	33.9	10.6	67.8	10.5	56.1	11.1	56.1	11.1

updating times ($F(6,114) = 6.3, P < 0.001$). Follow-up ANOVAs showed that when updating number increased to 3, updating times had most significant cumulate effect to the participants' performance ($F(3,79) = 15.0, P < 0.001$). These results are shown in Figure 3.

**Figure 3** Performance in different updating number and updating times conditions of Experiment 1. The data show cumulate effect of updating more items at one time.

1.3 Discussion

The current study observed that the performance decreased with the increase of updating times, indicating that the increase of updating times placed load on CE. Furthermore, updating times had cumulate effect on performance with the increase of updating character number. Thus, the results testified that the method of manipulating the load on CE is effective, and suggested that the CE played an important role in the verbal working memory updating task. In addition, the pattern of serial location effects generally resembled what have been reported in most of the memory researches.

It should be highlighted that the accuracy rate in the present study was much higher than that in earlier

study^[11]. It might be partly attributed to the emphasis on accuracy rate in the instruction. Moreover, the participants were not required to perform a secondary task at the same time.

2 Experiment 2

In order to identify the roles of CE and phonological loop in the verbal updating, we should add effective load on CE and slavery systems simultaneously in the working memory updating task. Experiment 1 suggested that increasing the number of updating items at one time could add effective load on CE. Using this method, we conducted Experiment 2 based on Morris and Jones' study^[11].

2.1 Method

(i) Participants. Fourteen undergraduate and graduate students (6 males, 8 females, 20–33 years of age, mean 25.1) from the Northeast Normal University took part in the study. All participants were right-handed, and had normal or corrected-to-normal vision. They were paid for their participation.

(ii) Apparatus and Materials. Stimuli were the same as those in Experiment 1.

(iii) Procedure. The stimuli were presented the same as that in Experiment 1. Participants were required to perform a secondary task (articulatory suppression) in one of the formal blocks, besides the updating task. In the articulatory suppression task, the participants were asked to whisper the word “de” at a rate of about twice per second throughout the whole block, including the recall periods. Participants should begin the secondary task first for several seconds till skilled, and then oper-

ated the two tasks at the same time. The order of presentation of the two conditions (no vs. add secondary task) was counterbalanced across participants. Practice trials were completed prior to the main experiment blocks. The participants were given the opportunity to take a break after the completion of the first block of trials.

Thus, the experiment involved a 3×4×2×4 within-participants design with the factors of updating number (updating character number: 1, 2, and 3), updating times (0, 1, 2, and 3), secondary task (no vs. add secondary task) and serial location (serial location of four recent items in a sequence: 1, 2, 3, and 4).

2.2 Results

Table 2 shows the responses for each condition scored as accuracy rate.

Repeated measures ANOVA compared the accuracy rates over the factors of updating number, updating times, secondary task, and serial location. The main effects of updating times ($F(3,27) = 11.5, P < 0.001$), secondary task ($F(1,9) = 8.6, P < 0.05$), and serial location ($F(3,27) = 7.5, P < 0.001$) were significant. Both the updating number×serial location and the updating times×serial location interactions were significant ($F(6,54) = 2.9, P < 0.05$, and $F(9,81) = 2.5, P < 0.05$). In addition,

there was a significant interaction between updating number and updating times ($F(6,54) = 8.8, P < 0.001$). Follow-up ANOVA showed that when updating number increased to 3, the updating times had most significant cumulate effect to performance decrement ($F(3,54) = 7.4, P < 0.001$). The results are shown in Figure 4.

Finally, both the updating number×secondary task and the updating times×secondary task interactions were not significant ($F(3,27) = 1.8, P > 0.05$, and $F(2,18) = 1.1, P > 0.05$), indicating that the increase of updating number and adding secondary task could lead to the decrements of participants' performance, but the effects of these two variables were independent. Similarly, the updating times and secondary task had also independent effects on the performance.

2.3 Discussion

The results showed that updating times has cumulate effect to the decrements of performance with the increase of updating number, indicating that increasing the number of updates could increase the load on CE, so as to make the performance sensitive to the change of updating times. It supported the conclusion of Experiment 1 and further proved that the method of controlling the load on CE is effective.

Table 2 Mean accuracy rates plus standard errors in different conditions of Experiment 2 (in percentage)^{a)}

Update	Times		Location 1		Location 2		Location 3		Location 4	
			M	SE	M	SE	M	SE	M	SE
1 character	0	no	98.5	3.3	89.2	8.3	95.4	5.7	95.4	5.7
		add	75.0	11.7	67.1	12.6	79.0	11.0	75.0	11.7
	1	no	60.0	13.2	58.3	13.3	60.0	13.2	66.7	12.7
		add	42.1	13.3	40.4	13.2	36.8	13.0	47.4	13.5
	2	no	55.0	13.4	56.3	13.3	61.3	13.2	72.5	12.0
		add	31.6	12.5	29.8	12.3	31.6	12.5	47.4	13.5
3	no	55.4	13.4	50.0	13.5	55.4	13.4	67.9	11.7	
	add	15.7	9.8	33.3	12.7	37.3	13.0	43.1	13.4	
2 characters	0	no	94.4	6.2	94.4	6.2	86.1	9.4	91.7	7.5
		add	61.9	13.1	59.5	13.3	66.7	12.7	59.5	13.3
	1	no	58.1	13.3	65.1	12.9	65.1	12.9	74.4	11.8
		add	31.1	12.5	31.1	12.5	40.0	13.2	44.4	13.4
	2	no	80.0	10.8	76.4	11.5	85.5	9.5	89.1	8.4
		add	79.1	11.0	74.6	11.7	76.1	11.5	71.6	12.1
3	no	66.7	12.7	70.8	12.3	75.0	11.7	72.9	12.0	
	add	55.2	13.4	46.6	13.4	58.6	13.3	53.5	13.4	
2 characters	0	no	83.0	10.2	93.6	6.6	85.1	9.6	87.2	9.0
		add	74.4	11.8	71.8	12.2	74.4	11.8	76.9	11.4
	1	no	74.5	11.8	78.7	11.1	74.5	11.8	74.5	11.8
		add	36.8	13.0	59.7	13.2	43.9	13.4	49.1	13.5
	2	no	46.3	13.4	61.2	13.1	49.3	13.5	59.7	13.2
		add	32.1	12.6	45.3	13.4	35.9	12.9	47.2	13.5
3	no	32.2	12.6	55.9	13.4	40.7	13.2	49.2	13.5	
	add	23.9	11.5	40.3	13.2	35.8	12.9	37.3	13.0	

a) "no/add" means whether the participants were required to perform a secondary task or not, besides the updating task.

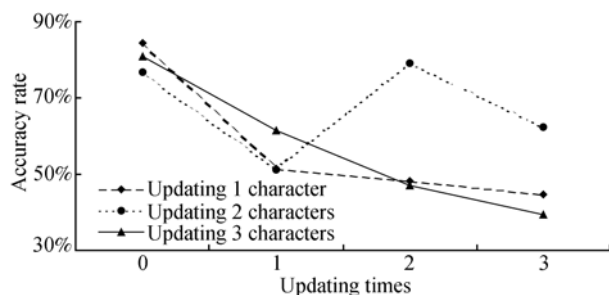


Figure 4 Performance in different updating number and updating times conditions of Experiment 2. The data show cumulate effect of updating more items at one time.

Furthermore, we got a similar result pattern as that in Morris and Jones' study^[11], that is, the main effects of both updating number and secondary tasks were significant whereas no interaction between them occurred. It suggested that memory updating required central executive resources but not the articulatory loop, and the serial recall aspect of the task required the articulatory loop but not the central executive. Thus, our data suggested, in agreement with the study by Morris and Jones^[11], that central executive and articulatory loop were responsible for the updating component and serial recall component respectively.

Researchers have used functional magnetic resonance imaging (fMRI) to investigate the neural correlates of the verbal working memory system, and demonstrated that the specific brain areas related to the rehearsal and storage of verbal material. Paulesu et al.^[25] reported evidence that frontal areas mediate the rehearsal of verbal material, whereas parietal areas mediate the storage of such material. Some researchers found that bilateral activation of the middle frontal gyrus of the dorsolateral prefrontal cortex (BA8/9) and the supramarginal gyrus of the inferior parietal cortex (BA40) were involved in the updating of verbal working memory for words^[26]. The activation of the middle frontal gyrus was argued to reflect executive control over the updating process, while the supramarginal gyrus might represent an amodal convergence zone binding modal representations of sensory information being retained in working memory. All these results supported the dissociation between the CE and the phonological loop and provided a strong support for the existence of a frontal-parietal verbal working memory circuit.

3 Experiment 3

In experiment 3, we employed the efficient method of

manipulating the load on CE and explored the role of CE and visuospatial sketchpad in the visuospatial working memory updating task. As we discussed earlier, central executive is important in the visuospatial updating. The data reported here could suggest the relationship between the functions of different sub-components in the visuospatial WM task.

3.1 Method

(i) Participants. Fifteen undergraduate and graduate students from the Northeast Normal University took part in the study. One participant had to be excluded due to adopting verbal strategy. The data from the remaining 14 participants (8 males, 6 females, 21–31 years of age, mean 22.8) were analyzed. All the participants were right-handed, and had normal or corrected-to-normal vision. They were paid for taking part in the study.

(ii) Apparatus and Materials. Stimuli were presented on a PIII 15" computer monitor. Light dot (1.5° of visual angle) were presented at one of the nine possible Locations: up, down, left, right, upper-left, downer-left, upper-right, downer-right, and center. For each participant, stimuli were pseudo-randomly drawn from nine possible Locations to form 111 Location sequences (15 sequences for the training block, and two formal blocks of 48 sequences).

(iii) Procedure. Participants sat in a dimly lit experimental chamber, 60 cm from the screen. An initial fixation cross (1.2°×1.2° of visual angle) was presented for 2000 ms in the center of the screen. Then the light dots at different Locations were sequentially shown. Each dot was presented for 200 ms on the screen followed by a blank screen of 800 ms. An input screen was displayed at the end of a sequence. The participants were instructed to recall the locations of last three dots, and to respond with keyboard, using the number key on the right part of a keyboard to represent the different nine locations. There was no time limit for typing the response. However, the participants were instructed to respond as rapidly as possible without sacrificing the accuracy rate. The average inter-trial interval (ITI) was 1000 ms (varying randomly between 900 and 1100 ms). The length of sequences was 3 dots at least, and would change with the variation of updating times.

Participants were instructed to perform a secondary task (spatial tapping task) in one of the formal blocks, besides the updating task. In the spatial tapping task, the participants were required to tap four corners of a pane

(9.2 cm×8.9 cm) at a rate of one corner per second. The board was concealed from vision to avoid visual distraction and to increase spatial monitoring when performing the task. Participants should begin the tapping task first for several seconds till skilled, then performed the two tasks at the same time. The order of presentation of the two conditions (no vs. add secondary task) was counterbalanced across participants. Practice runs were completed prior to the main experimental blocks. The participants were given the opportunity to take a break after the completion of the first block of trials.

Figure 5 shows the examples of stimulus displays in the updating one light dot condition. When the updating dot number was two, two dots were presented in turn at a very rapid, but discernible speed after the third dot. The participants had to update two items in their working memory content at one time, and recalled the three recent locations of light dots.

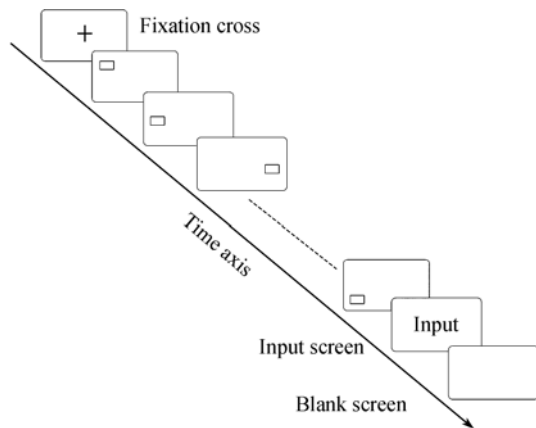


Figure 5 Examples of stimulus displays from Experiment 3.

After finishing the experiment the participants were asked to fill in a short questionnaire about the strategy they have used in the experiment. If someone used verbal strategy, such as changing the location to number information, his or her data will be deleted.

Thus, the experiment involved a 2×4×2×3 within-participants design with the factors of updating number (updating location number: 1 and 2), updating times (0, 1, 2, and 3), secondary task (no vs. add secondary task) and serial location (1, 2, and 3).

3.2 Results

Table 3 shows the responses for each condition scored as accuracy rate.

A repeated measures ANOVA compared the accuracy rates over the factors of updating number, updating times, secondary task, and serial location. The main effects of updating number ($F(1,13) = 41.9, P < 0.001$), updating times ($F(3,39) = 3.5, P < 0.05$), and serial location ($F(2,26) = 7.8, P < 0.01$) were significant. The interaction between updating number and serial location was significant ($F(2,26) = 4.7, P < 0.05$). Moreover, the interaction between updating number, updating times and serial location was significant ($F(3,39) = 3.2, P < 0.05$). The four-way ANOVA revealed also a significant interaction between updating number and updating times ($F(3,39) = 8.2, P < 0.001$). Follow-up ANOVAs showed that when updating number increased to 2, updating times had most significant cumulate effect on the performance ($F(3,55) = 5.8, P < 0.01$). The result is shown in Figure 6.

Table 3 The mean accuracy rates plus standard errors in different conditions of Experiment 3 (in percentage)^{a)}

Update	Time		Location 1		Location 2		Location 3	
			M	SE	M	SE	M	SE
1 location	0	no	79.1	10.9	89.5	8.2	89.5	8.2
		add	61.6	13.1	71.2	12.2	76.7	11.4
	1	no	72.7	12.0	86.4	9.2	92.1	7.3
		add	66.3	12.7	73.7	11.8	80.0	10.8
	2	no	72.1	12.1	89.5	8.2	91.9	7.3
		add	68.3	12.5	77.8	11.2	88.9	8.5
3	no	81.8	10.4	90.9	7.8	87.9	8.8	
	add	65.4	12.8	74.1	11.8	80.3	10.7	
2 locations	0	no	79.7	10.9	84.4	9.8	93.8	6.5
		add	62.5	13.0	71.6	12.1	79.6	10.9
	1	no	63.1	13.0	53.9	13.4	64.6	12.9
		add	67.2	12.6	59.4	13.2	68.8	12.5
	2	no	61.2	13.1	55.3	13.4	61.2	13.1
		add	46.6	13.4	51.1	13.4	55.7	13.4
	3	no	42.3	13.3	44.7	13.4	49.4	13.4
		add	55.6	13.4	58.0	13.3	60.5	13.1

a) "no/add" means whether the participants were required to perform a secondary task or not, besides the updating task.

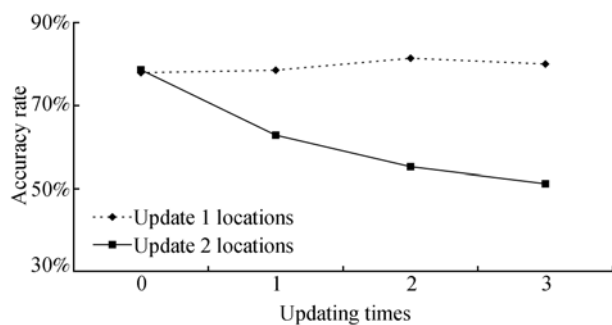


Figure 6 Performance in different updating number and updating times conditions of Experiment 3. The data show cumulate effect of updating more items at one time.

Finally, both the updating number \times secondary task and the updating times \times secondary task interactions were significant ($F(1,13) = 9.1, P < 0.05$, and $F(3,39) = 4.3, P < 0.05$). Follow-up ANOVAs revealed that when updating one location, the performance decreased significantly with the secondary task ($F(1,13) = 9.9, P < 0.01$); When updating two locations, the performance did not change significantly, whether the participants performed the secondary task or not (Figure 7). Similarly, when there was no updating, the performance decreased significantly with the secondary task ($F(1,13) = 22.7, P < 0.001$); when updating times increased, the performance did not change significantly, whether the participants performed the secondary task or not (Figure 8).

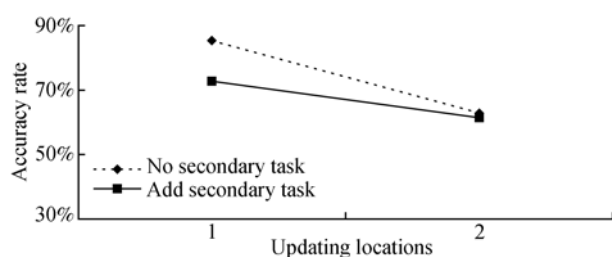


Figure 7 Performance influenced by the updating number and secondary task in Experiment 3. The data show the interaction between the effect of updating item number and the effect of the secondary task.

3.3 Discussion

As in Experiments 1 and 2, updating times had cumulate effect on performance with an increase in updating item number. Therefore, these results indicated that the method of controlling the load on CE is effective, and demonstrated that updating needs the control processing of CE. With the increase of load on CE, the performance was impaired, no matter whether there was a secondary task or not (Figures 7 and 8). However, the degree of decrement was substantially different. If there was no

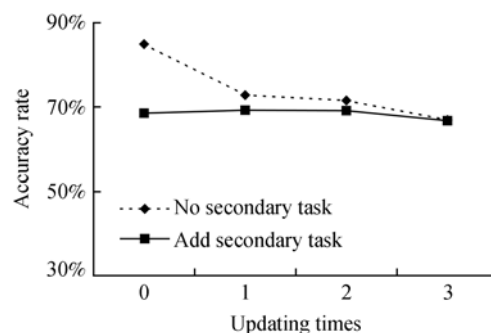


Figure 8 Performance influenced by updating times and secondary task in Experiment 3. The data shows the interaction between the effect of updating times and the effect of secondary task.

secondary task, the slope of performance went down more sharply than that with the secondary task. It suggested that the performance was less accurate when the load on CE was high, and the performance would not decrease much when adding the secondary task.

Moreover, both the updating number and updating times had significant interactions with the secondary task. The updating number and times controlled the load on CE, and the secondary task added load on visuospatial sketchpad. Therefore, we proposed that CE and visuospatial sketchpad together dealt with the updating component, while the serial recall component needed the visuospatial sketchpad only, since CE had no store function. This is further supported by a study by Miyake and Friedman, who examined the extent to which various aspects of executive functioning were involved in spatial processing^[27]. Their results suggested that executive processes were implicated in a wide range of spatial tasks, which supported that the visuospatial sketchpad might be closely tied to the central executive.

Compared to the study by Fisk and Sharp^[24], we did find that the spatial recall was impaired even on long sequences, indicating that the updating actually occurred on the longer sequences. They failed to find the updating function in longer sequences, which might be attributed to the separation of load on CE and visuospatial sketchpad.

4 General discussion

The objective of this study was to compare the process of updating verbal and visuospatial WM. Our results suggested that the CE plays an important role in the working memory updating task. In the verbal working memory updating task, the central executive system took

charge of the updating component, while the phonological loop was responsible for the serial recall component. In the visuospatial working memory updating task, central executive and visuospatial sketchpad dealt with the updating component together, while the visuospatial sketchpad was responsible for the serial recall component by itself. Furthermore, the similar pattern of results in the three experiments demonstrated that the method of changing the number of updating items was effective in controlling the load on CE. Manipulating the CE function directly, such a method can also avoid a response selection bottleneck and a strategy trade-off between primary and secondary tasks in the dual-task methodology^[28].

Morris and Jones found that the number of updates did not affect performance^[11]. They inferred that the executive could either perform several updates in rapid sequence without overloading its capacity or could have a very rapid ‘recovery’ rate when performing such operations. However, we did find that the updating times had cumulative effect on performance decrements with the increasing number of updates to change the load on CE, which was not found in their experiment. Kusak et al. attributed this to the variance in the memory load^[10]. This explanation may not be appropriate, since we merely required the participant to recall the three or four recent items (which was the same as that in Morris and Jones’ study). According to the working memory model outlined by Baddeley^[2], the episodic buffer comprises a limited capacity system that provides temporary storage of information held in a multi-modal code, which is capable of binding information from the subsidiary systems, and from the long-term memory, into a unitary episodic representation. It is assumed that the episodic buffer can be accessed by the central executive through the medium of conscious awareness. Based on the new WM model, it might be speculated that the updating of working memory needs episodic buffer, and the control ability of central executive is limited. In the working memory updating task, when adding a new item, a shift of the rehearsal set is needed, which involves assigning

a new ordinal tag to the item and all the tags must be refreshed at each update. The old items and newer items in each shift are stored in the episodic buffer and all the operations are performed in it. It might require modulation and coordination by the central executive system because the items after each rehearsal are different. Participants can perform updating task easily if the current task is under the control ability of CE. Their performance might be impaired when the task is beyond the CE’s capabilities. Thus, central executive may reflect a basic control capability, which is critical across a wide range of working memory tasks.

In summary, the present study suggests that the verbal and spatial working memory updating processes have different patterns, and that CE and slavery systems play different roles in the working memory updating task. Moreover, whereas the span of verbal working memory appears to be larger than that of visuospatial working memory, people might have different temporary store capability in these two types of updates. The survey conducted after the verbal working memory updating task suggested that the participants always read silently to assist memorizing, and the most frequent mistake was homophonous confusion. The survey conducted after the visuospatial working memory updating task revealed that the participants used images to assist memorizing, including imagining a figure, drawing a line between two dots, or imagining the movement of dots. In an event-related fMRI study, researchers investigated the neural substrates underlying updating phases, and the influence of grouping and proactive interference on updating phases^[29]. They found that the episodic information related to environment is automatically encoded during the encoding period, and such an operation could not be inhibited. That reminds us that the verbal WM updating might use the phonic encoding, while the visuospatial WM updating might use the episodic encoding. By drawing increasingly specific exploration of similarity and difference between verbal and visual-spatial updating in future, research into the updating of working memory will make major advances.

- 1 Baddeley A. Recent developments in working memory. *Curr Opin Neurobiol*, 1998, 8: 234–238
- 2 Baddeley A. The episodic buffer: A new component of working memory? *Trends Cogn Sci*, 2000, 4: 417–423
- 3 Repovš G, Baddeley A. The multi-component model of working memory: Explorations in experimental cognitive psychology. *Neurosci*, 2006, 139: 5–21

- 4 Baddeley A. Exploring the central executive. *Q J Exp Psychol*, 1996, 49A: 5–28
- 5 Collette F, van der Linden M. Brain imaging of the central executive component of working memory. *Neurosci Biobehav Rev*, 2002, 26: 105–125

- 6 Miyake A, Friedman N P, Emerson M T, et al. The unity and diversity of executive functions and their contributions to complex “frontal lobe” tasks: A latent variable analysis. *Cogn Psychol*, 2000, 41: 49–100
- 7 Salmon E, van der Linden M, Collette F, et al. Regional brain activity during working memory task. *Brain*, 1996, 119: 1617–1625
- 8 van der Linden M, Collette F, Salmon E, et al. The neural correlates of updating information in verbal working memory. *Memory*, 1999, 7: 549–561
- 9 Kiss I, Pisio C, Francois A, et al. Central executive function in working memory: Event-related brain potential studies. *Cogn Brain Res*, 1998, 6: 235–247
- 10 Kusak G, Grune K, Hagendorf H, et al. Updating of working memory in a running memory task: An event-related potential study. *Int J Psychophysiol*, 2000, 39: 51–65
- 11 Morris N, Jones D M. Memory updating in working memory: The role of the central executive. *Br J Psychol*, 1990, 81: 111–121
- 12 Ravizza S M, Behrmann M, Fiez J A. Right parietal contributions to verbal working memory: Spatial or executive? *Neuropsychologia*, 2005, 43: 2057–2067
- 13 Rudner M, Fransson P, Ingvar M, et al. Neural representation of binding lexical signs and words in the episodic buffer of working memory. *Neuropsychologia*, 2007, 45: 2258–2276
- 14 Pollack I, Johnson I B, Knaff P R. Running memory span. *J Exp Psychol*, 1959, 57: 137–146
- 15 Avons S E, Nunn J A, Chan L, et al. Executive function assessed by memory updating and random generation in schizotypal individuals. *Psych Res*, 2003, 120: 145–154
- 16 van der Linden M, Brédart S, Beerten A. Age-related differences in updating working memory. *Br J Psychol*, 1994, 85: 145–152
- 17 Smith E E, Jonides J, Koeppel R A. Dissociating verbal and spatial working memory using PET. *Cereb Cortex*, 1996, 6: 11–20
- 18 Zurowski B, Gostomzyk J, Grön G, et al. Dissociation a common working memory network from different neural substrates of phonological and spatial stimulus processing. *NeuroImage*, 2002, 15: 45–57
- 19 Awh E, Jonides J, Smith E E, et al. Dissociation of storage and rehearsal in verbal working memory: Evidence from positron emission tomography. *Psychol Sci*, 1996, 7: 25–31
- 20 Fiebach C J, Rissman J, D’Esposito M. Modulation of inferotemporal cortex activation during verbal working memory maintenance. *Neuron*, 2006, 51: 251–261
- 21 Mottaghy F M. Interfering with working memory in humans. *Neuroscience*, 2006, 139: 85–90
- 22 Morris N. Exploring the visuo-spatial scratch pad. *Q J Exp Psychol*, 1987, 39A: 409–430
- 23 Logie R H, Marchetti C. Visuo-spatial working memory: Visual, spatial or central executive? In: Logie R H, Dennis M, ed. *Mental Images in Human Cognition*. Amsterdam: North Holland Press, 1991. 105–115
- 24 Fisk J E, Sharp C A. The role of the executive system in visuo-spatial memory functioning. *Brain Cogn*, 2003, 52: 364–381
- 25 Paulesu E, Frith C D, Frackowiak R S J. The neural correlates of the verbal component of working memory. *Nature*, 1993, 362: 342–345
- 26 Clark C R, Egan G F, McFarlane A C, et al. Updating working memory for words: A PET activation study. *Human Brain Map*, 2000, 9: 42–54
- 27 Miyake A, Friedman N P, Rettinger D A, et al. How are visuo-spatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. *J Exp Psychol: Gen*, 2001, 130: 621–640
- 28 Hegarty M, Shah P, Miyake A. Constraints on using the dual-task methodology to specify the degree of central executive involvement in cognitive tasks. *Mem Cognit*, 2000, 28: 376–385
- 29 Berger J S, Goldstein J, Postle B R, et al. Updating task reveals episodic coding in working memory. *Annual Meeting of the Cognitive Neuroscience Society, Washington D.C., April, 1999*. 11–13