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

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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.

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 articulary 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 domains. 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

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

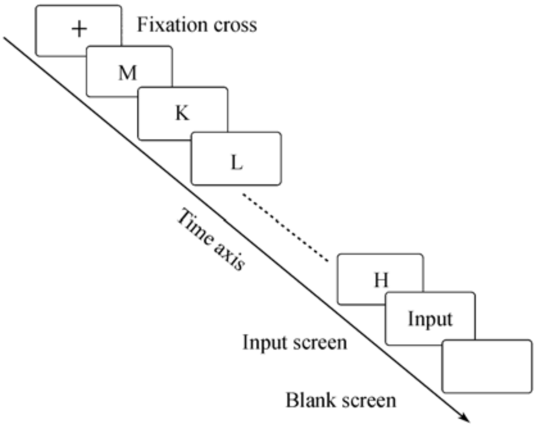
Updating has been testified as one of the important executive functions[4−6]. Many brain imaging researches have found that activities in right mid-dorsal prefrontal cortex (PFC), left middle frontal regions, and right frontal pole (Broadman areas, BA9, BA46/10) are associated with updating function 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 observand 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.

(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 breviary 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 equiprobablly, 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.



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).

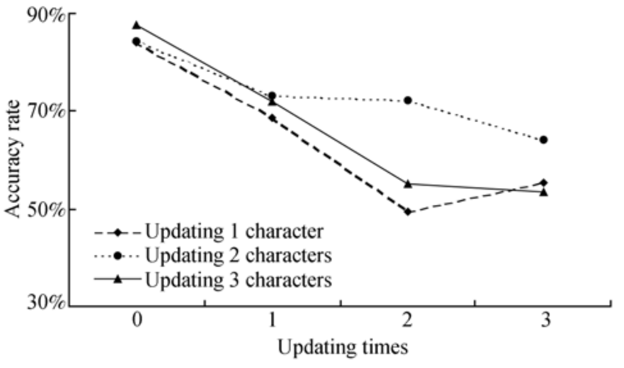
The responses for each condition were scored as accuracy rate (Table 1).

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

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.



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

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].

(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 operated 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).

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 tiingn we30.1541 ti P

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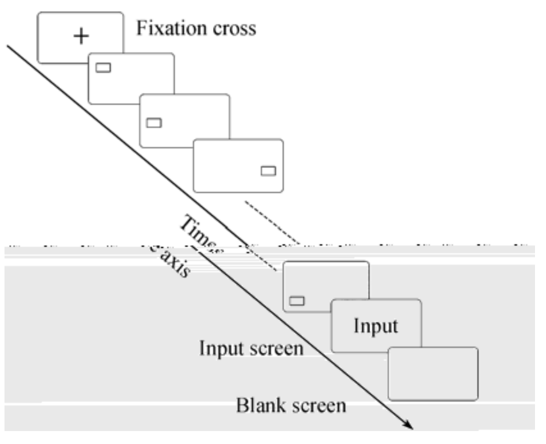
(9.2 cm×8.9 cm) at a rate of one corner per second. The board was concealed from vision to avoid visual distraction and to increase spatial monitoring when performing the task. Participants should begin the tapping task first for several seconds till skilled, then performed the two tasks at the same 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.



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).

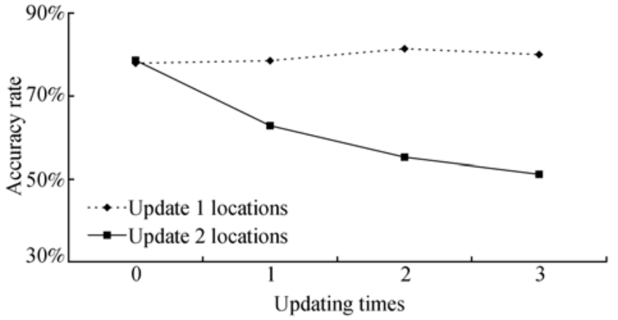
Table 3 shows the responses for each condition scored as accuracy rate.

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.

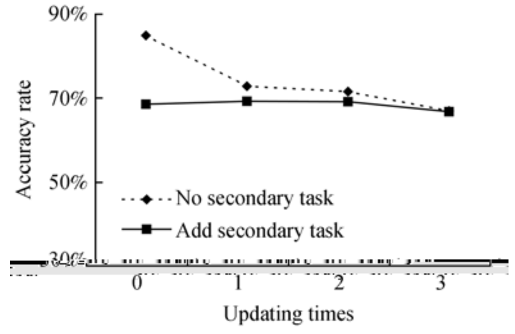
The mean accuracy rates plus standard errors in different conditions of Experiment 3 (in percentage)[a)]

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.

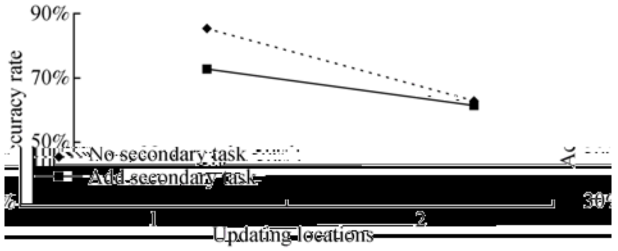


Performance in different updating number and updating times conditions of Experiment 3. The data show cumulate effect of updating more items at one time.



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.

Finally, both the updating number×secondary task and the updating 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).



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.

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 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

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