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# Declarative memory affects procedural memory: The role of semantic association and sequence matching

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ABSTRACT

Declarative memory and procedural memory have their own independent information processing channels, but also share common processing mechanisms. Converging evidence recently shows that declarative learning can inhibit the performance of procedural memory. However, other studies also show that there may be semantic association effect and sequence expectation effect. We assumed that this interference effect of declarative memory on procedural memory could vanish or even be transformed into the enhancing effect when there was semantic association or both semantic association and sequence matching existed between two tasks. Experiment 1 examined the role of semantic association in the influence of declarative memory on procedural memory. We found that the performance of the semantic association group was significantly better than that of the baseline group, while the performance of the semantic independent group was significantly worse than that of the baseline group. In Experiment 2, based on semantic association, the role of sequence matching in the impact of declarative memory on procedural memory was tested. As a result, the accuracy of the sequence matching group was significantly higher than that of the baseline group, while the accuracy of the sequence mismatched group was not significantly different from that of the baseline group. The results of the two experiments suggest that the effect of declarative memory on procedural memory is not a fixed relationship. It is modulated by semantic association and sequence matching between two tasks. Declarative memory can interfere with procedural memory when two tasks have no semantic association, however, when there is semantic association the interference effect can vanish. Further, when both semantic association and sequence matching exist, the interference effect can be reversed into an enhancing effect.

We are learning new information every day. The process involving information acquisition and its extraction after a long period of time (more than 1 min) is called long-term memory. Anderson (1980) divided long-term memory into declarative memory and procedural memory to reflect the different characteristics of the stored information. Procedural memory ("knowing how"), also known as skill memory, is a long-term memory system responsible for procedural knowledge. This system involves the acquisition, storage and use of tacit knowledge (Gabrieli, 1998; Squire & Zola, 1996; Willingham, 1998), which is the basis for various perceptual, motor and cognitive skills. It subserves sequencing (Fletcher et al., 2004; Willingham, Salidis, & Gabrieli, 2002), navigation (e.g., "response" learning and strategy in rodent; Packard, 2009) and probability classification (Knowlton, Mangels, & Squire, 1996; Poldrack et al., 2001). There are two main characteristics of procedural memory. One is its need for repeated practice. Procedural learning involves a series of complex processes. In the early stage, procedural learning proceeds gradually with the repetition of stimuli and the practice of skills (Gagné & Cohen, 2016; Karni, 1996; Karni et al., 1998). However, once you have mastered this knowledge, you can quickly operate your skills. The other one is that the acquisition of procedural knowledge is an unconscious process that is difficult to transfer to another person by means of writing it down. As opposite to implicit procedural memory, declarative memory refers to the memory of declarative knowledge that we can contact (or access) through conscious processes. Researchers have further subdivided declarative memory into episodic memory (e. g., recalling the events that occurred in our lives) and semantic memory (memory of semantic knowledge). Semantic knowledge involves the knowing of certain events such as the things we are sitting on may (or may not) be chairs, and other similar facts and definitions, including world knowledge, object knowledge, language knowledge and concept priming. Semantic processing is the main function of declarative memory (both episodic memory and semantic memory). Tulving and Markowitsch (1998) argued that encoding of information into the episodic system depended primarily on

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the semantic system which was also indispensable to encode information into the semantic system.

Traditionally, the procedural and declarative memory system have been viewed as dissociated neurally and functionally (e.g., DeCoteau & Kesner, 2000; Kesner, Bolland, & Dakis, 1993; Packard, Hirsh, & White, 1989). Studies of the brain mechanism of each memory system have revealed that the two memory systems depend on different neural circuits and brain systems. The procedural memory system is supported by a net-like brain structure which includes parts of the basal ganglia, cerebellum and frontal cortex, including premotor cortex and posterior parts of Broca's area (e.g., BA 44) (Gabrieli, 1998; Knowlton et al., 1996; Robertson, Tormos, Maeda, & Pascual-Leone, 2001; Ullman, 2004; Ullman & Pierpont, 2005). Declarative memory is largely mediated by the hippocampus and structures near medial temporal lobe (Eichenbaum, 2004; Squire et al., 2004), neocortex (Indefrey & Cutler, 2004; Martin & Chao, 2001), and parts of prefrontal region (e.g., in the region of Brodmann's Areas 45/47; Buckner & Wheeler, 2001; Wagner et al., 1998). Studies on patients with brain injury have also showed that the procedural memory system is only slightly impaired when the declarative memory system is impaired, and vice versa (Cohen & Squire, 1980; Gabrieli, Corkin, Mickel, & Growdon, 1993; Willingham, 1997; Willingham et al., 2002). For example, diseases such as Alzheimer's disease can affect patients' ability to learn and recall facts and events, whereas their ability to learn new skills is relatively preserved (see Gabrieli et al., 1993). In contrast, in other diseases such as Huntington's disease, patients' ability to learn and recall facts and events is relatively maintained, but their ability to learn new skills is damaged (see Gabrieli, Stebbins, Singh, Willingham, & Goetz, 1997). From these studies, we can find that anatomically distinct neural circuits are involved in the processing of declarative and procedural memory. This seems to indicate that the two memory systems are dissociated and work separately.

Over the past two decades or so, however, the concept of independent memory system has gradually been challenged. The neuroimaging investigations with healthy people have revealed that the procedural and declarative memory system share common neural networks (Hardwick, Rottschy, Miall, & Eickhoff, 2013). For example, activation of the medial temporal lobe (MTL), a brain region associated with declarative memory processing, is related to activation of the striatum which is associated with the processing of procedural memory (see Poldrack et al., 2001). The hippocampus is a brain structure on which the declarative memory system depends, but some fMRI researches have found significant hippocampal activation is not only observed in the course of an explicit motor sequence learning task (Albouy et al., 2008), but also exists under implicit conditions (Schendan, Searl, Melrose, & Stern, 2003). Therefore, rather than being independent, there is functional connection between the two memory systems. Studies using memory interference paradigms also support the idea of interaction. In the study of Brown and Robertson (2007), a declarative memory task (learned a series of words) was introduced immediately after performing a serial reaction time task (responded to a repeating 12-item sequence, 2-3-1-4-3-2-4-1-3-4-2-1, by pressing the appropriate button on the pad). After a period of wakefulness, performance of procedural memory was inhibited. This indicates that declarative memory task inserted during the encoding stage of procedural memory can interfere with procedural memory. Using a finger-to-thumb opposition sequence (FOS) task (Karni et al., 1995) as the procedural task, Gagné and Cohen (2016) obtained similar results. In their study, participants were first trained on the FOS task, in which participants were instructed to open the palm of the right hand and repeated a finger sequence of 4-2-3-1-4 (1 = index finger, 2 = middle finger, 3 = ring finger and 4 = little finger) as quickly and accurately as possible. After that they were given a visual search task and asked to locate specific targets in two pictures. One day later, only half of participants directly tested on the FOS task, and the other half conducted a declarative task (recalling the spatial location of some visual scenes viewed the day before) prior to the retest of the FOS task. As a result, the performance of the group that conducted a declarative recall task before performing the procedural recall task was significantly worse than that of the group that directly performed the FOS recall task. These results show that the interference effect between procedural and declarative memory may be not time limited. It can occur not only in the encoding stage but also in the retrieval stage of procedural memory. The interference effect between two kinds of memory systems has been found in these studies, but the declarative and procedural tasks in their experiments were separated from each other, without semantic association. In this case, the interaction between the two memory systems can not be fully proven.

In everyday life, it is easy to find that previously acquired knowledge may inhibit skill learning. For example, if you learn the theory of driving automatic transmission cars before learning to drive a stick shift, then you will unconsciously use the driving knowledge of automatic car such as not treading on clutch before shifting (declarative memory) in driving manual transmission car, and therefore inhibit the formation of driving skills with manual transmission car (procedural memory). Besides, you can also find that the existing experience may support skill learning. For example, acquiring swimming skills can be more effective on the basis of certain swimming knowledge (relevant to swimming skills). Before learning to swim, we may have read some related books and memorized some essentials of movement (declarative memory). With continuous practice, we can turn this knowledge into swimming skills (procedural memory) and truly learn to swim. These examples in everyday life suggest that both the procedural memory system and the declarative memory system are complex. The relationship between them may not be a simple interference relationship, and semantic association may play an important role in regulating the relationship between them.

In some laboratory studies, researchers have reported that semantic association has an impact on the memory of non-semantic materials. When there is semantic association between the encoding mode and the content to be remembered, it is usually easier to remember the target content (Craik & Lockhart, 1972). Demb et al. (1995) also obtained evidence for it. They found individuals using semantic coding performed better than those who did not use semantic coding. In addition, semantic association between the distractor and the target stimulus can also affect the performance of the target task. Rosinski (1977) conducted a study about picture-word interference. In his experiment, participants were asked to label pictures (line drawings) on which three kinds of words might be superimposed. These kinds of words were as follows: word that was the corresponding label of the picture (e.g., word "dog" on the picture of a dog); word that was paired randomly with picture but came from the same semantic category as picture (e.g. word "cat" on the picture of a dog); word consisting of a consonant-vowel-consonan trigram (e.g. cvc). As a result, as compared with the control condition without word superimposed on the picture, the performance of the label condition was the best, while that of the random pairing condition and the trigram condition were all worse. This reveals that the processing of picture information is affected by semantic processing, and the semantic processing associated with the picture can promote picture's processing. These studies above indicate that task performance is better if there is a high semantic association between the coding mode or the task-unrelated item and the target rather than without semantic association. Therefore, we speculate that semantic association between two kinds of memory tasks may be a critical regulator in the influence of declarative memory on procedural memory.

Procedural memory is a memory of action skills consisting of a series of actions or steps. Declarative memory may also involve sequences, such as memory of a series of words. The important role of sequential cues has been found in sequence learning tasks. In this context, many studies have shown that when the presentation of the target stimulus follows a predicted sequence, people can respond faster than sequences that are randomly generated (Cohen, Ivry, & Keele, 1990; Mayr, 1996; Nissen & Bullemer, 1987). Nissen and Bullemer (1987) claimed that participants could not only anticipate a series of reactions but learn where to expect the next stimulus due to a repeating sequence. In addition to the benefits of this sequential expectation, several studies also have argued that when presenting two items successively, the location matching relationship between items can affect participants' performance. Using a priming paradigm, Vaquero, Fiacconi, and Milliken (2010) found when the location of the prime did not match that of the probe target (Exp 1), the performance of participants was poor. However, almost all participants perform better when there was a location matching relationship between the prime and the probe target (Exp 2). In their study, the priming item served as a cue to detect the target, and when the priming item matched the target item in spatial location, the task performance of the target item could be more efficient. These researches indicate the sequential cues in sequence response tasks and the spatial location cues of items when two related items are presented successively can be effectively grasped. Accordingly, when we acquire a procedural sequence followed by a declarative sequence related to it semantically, the sequential expectation effect may be observed. In this case, individuals might expect that the presentation order of items in the declarative sequence matched that of the procedural sequence and finally be benefit from it because of the high association between two kinds of semantic information.

Our brain is a very complex information processing system. Previous studies have revealed the separation of declarative and procedural memory in brain mechanisms, and also have discovered the underlying neural mechanisms supporting their interaction. Specific researches on the interaction between the two kinds of memory have found that declarative memory can interfere with procedural memory. However, these studies are primarily based on the fact that the two memory tasks are independent, and there is no semantic association between them. Some studies have argued that semantic association can facilitate the performance of memory tasks, and sequence matching can also promote the completion of tasks through expectation effects. Language is a complex system with semantic identification which exists only in human beings. When humans want to mimic the sequence of actions, the generation of language enables humans to complete the learning of motor skills. What's more, the participation of language makes human's motor skill learning more complicated and efficient. Many kinds of action sequences in humans, such as martial arts routines, gymnastics, figure skating, are highly integrated bodies with declarative knowledge and procedural knowledge. For understanding the learning process of these motor skills, certain questions have to be clarified. For example, under what conditions can declarative memory interfere with or facilitate procedural memory? When do these two kinds of memory do not affect each other? All of these questions are discussed in the current study.

## 1. Experiment 1: the role of semantic association in the influence of declarative memory on procedural memory

In Experiment 1, the role of semantic association in the influence of declarative memory on procedural memory was tested by comparing the sequential recall performance of the same procedural task among the semantic association group, the semantic independent group and the non-semantic group.

### 1.1. Method

We used a single-factor between-groups design. The independent variable was semantic association, which was divided into three levels: semantic association, semantic independent and non-semantic (baseline).

#### 1.1.1. Participants

Seventy-six students were randomly recruited. Participants (26 men, 50 women) were between the age of 18 and 25 years (mean = 20.1 years, SD = 3.71) and had a normal or corrected-to-normal vision. All participants had not participated in any action training or similar memory experiments before. All were paid for their participation. After deleting one invalid data (withdrew in the halfway), seventy-five participants' data were included in statistical analysis. All participants were randomly divided into three groups with 25 people in each group.

#### 1.1.2. Materials

Forty actions were selected as alternative materials and the difficulty of each action was evaluated on a 5-point scale ranging from not at all difficult (1) to very difficult (5) by 25 students. These students were asked to write down five words most related to each of these forty actions meanwhile.Ten actions with difficulties between 1.00 and 2.00 (motor difficulty: M = 1.62, SD = 0.29) were randomly chosen to ensure that participants can easily master these actions. They were randomly fixed as a set of the action sequence.

Word with the most frequency was selected for each action. Among these forty words, ten words corresponding to the ten selected actions constituted an associated the word-list. The presentation order of words completely matched that of the actions in action sequence, including Squatting down, leg lifting, waving hands, jumping, running, rope skipping, quick marching, leg pressing, raising arms, expanding chest. For words that correspond to the remaining thirty actions, ten words were randomly selected from them to form a list of unassociated words. These words, in order, were fencing, soccer, bunker, swimming, inverted, Kung Fu, weightlifting, cooking, shotting, piano.

#### 1.1.3. Procedure

To ensure that the control of declarative tasks under the conditions of semantic association and semantic independent was successful, we performed the following operations before the formal experiment. Fourteen college students were randomly selected and divided into two groups on average. One group learned semantic association words, the other group learned semantic independent words. The materials were the same as words in the associated word-list and words in the unassociated word-list. Both groups were only allowed to learn these words once. Following a 2-min masking task, participants were asked to recall, in the presentation order, as many of the words they learned before as possible within 2 min. As a result, there was no significant difference in word recall accuracy between the two groups, $F_{(1,12)} = 0.05$, $p = .83$. This result suggests that the control of declarative tasks is successful.

The formal experiment included 3 sessions consisting of the action sequence learning task, the word-list task and the action sequence recollection task. A masking task (simple arithmetical task) with 2 min was conducted between each two sessions. The time interval between the first test (session 1) and the retest (session 2) on the action sequence was equal among all groups. After experiment, participants were asked whether they had figured out the intention of experiment and given explanation of the true purpose of experiment.

The action sequence learning task: All participants were taught a set of the action sequence consisting of 10 simple actions by one experimenter. First of all, the experimenter decomposed these 10 actions to participants. Secondarily, participants were asked to imitate them for 3 times. A minute for rest was given following each imitation. After learning for 3 times, a masking task with 2 min was presented. Finally, all participants were required to recall these ten actions sequentially as quickly and accurately as possible. We calculated the accuracy and completion time of each participant.

The word-list task: Participants in the semantic association group were asked to learn words semantically associated with actions, the semantic independent group was asked to learn words semantically unassociated with actions. In the baseline group, the word-list task was replaced by a task requiring them to perform simple arithmetic

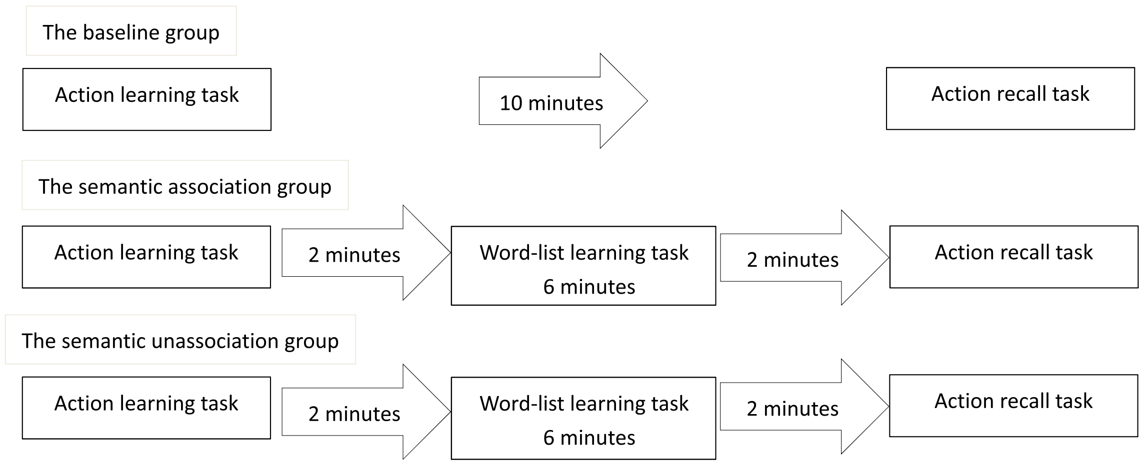


**Fig. 1.** Experimental design in Experiment 1.

operations. Instructions were presented on a 23-inch computer screen placed directly in front of the seated participants, approximately 45 cm from their chest. A single word from a list of ten words with 32-point Courier New font was presented in the center of the screen for 3 s. The word was then removed and replaced by another word also drawn from the list of ten words. After all ten words presented, participants were asked to perform a masking task for one to 2 min. After that, participants were required to recollect these words according to the order that presented before by oral reporting in 2 min.

The action sequence recollection task: Participants were retested on the primary task (session 1), which required them to recall the sequence consisting of all learned actions quickly and accurately in 5 min. We recorded the correct recollection rate and completion time of each participant. The experimental design is shown in Figure 1.

### 1.2. Results

The first test and retest results of the action sequence for the three subject groups are shown in Table 1. A one-way ANOVA was conducted on the accuracy and completion time of the first test for semantic association. There were no significant difference across the three subject groups both in accuracy and completion time (for accuracy, $F_{(2,72)} = 2.70$, $p = .07$, $\eta_p^2 = 0.07$; for completion time, $F_{(2,72)} = 0.52$, $p = .60$, $\eta_p^2 = 0.01$) of the first action recall, suggesting no significant difference in procedural memory performance among the three groups that could account for differences on the random grouping variable.

A one-way ANOVA was conducted on the accuracy and completion time of the retest for semantic association. For accuracy, this analysis yielded a significant main effect of semantic association, $F_{(2,72)} = 33.43$, $p < .001$, $\eta_p^2 = 0.48$. Post hoc comparisons depicted that the accuracy of the semantic association group was significantly higher than that of the baseline group, $p = .006$, it was also significantly higher than that of the semantic independent group, $P < .001$, and the accuracy of the baseline group was significantly higher than that of the semantic independent group, $p < .001$. For completion time, a significant main effect of semantic association was observed, $F_{(2,72)} = 18.42$, $p < .001$, $\eta_p^2 = 0.34$. Post hoc comparisons depicted that the completion time of the semantic association group was significantly shorter than that of the baseline group, $p = .019$, it was also significantly shorter than that of the semantic independent group, $P < .001$, the completion time of the baseline group was significantly shorter than that of the semantic independent group, $p = .001$.

### 1.3. Discussion

The aim of Experiment 1 was to examine the role of semantic association in the influence of declarative memory on procedural memory. The retest results showed that the performance of the semantic independent group was inferior to that of the baseline group both in accuracy and completion time. This indicates that unassociated words presented during the interval between the first test and the retest of procedural memory can act as distractors, causing the declining retest results of procedural memory. Semantic associated words do interfere with the performance of procedural memory, which is consistent with the results of Gagné and Cohen (2016). The reason for this interference effect may be that the two memory systems compete for common processing resources such as the hippocampus through their respective processing channels (for detailed discussion, see Gagné & Cohen, 2016).

In addition, the semantic association group recalled better than the baseline group. This means that when a declarative task is semantically associated with a procedural task, the interference effect of declarative memory on procedural memory can be reversed into an enhancing effect, which verifies our experimental hypothesis. These results of Experiment 1 suggest that in the case of semantic association, there is a binding effect between declarative memory and procedural memory for their similarity. And the resource usage patterns of the two can change from the competition mode (interfere with each other) to the sharing mode (support each other).

**Table 1**
Mean and standard deviation (in parenthesis) for accuracy (%), and completion times (ms) for different semantic relevance in Experiment 1.

| | | Baseline group | Semantic association group | Semantic independent group |
|---|---|---|---|---|
| Accuracy | The first test | 83.20 ± 8.52 | 79.20 ± 7.59 | 84.40 ± 8.70 |
| | The retest | 84.80 ± 9.63 | 92.40 ± 7.23 | 70.80 ± 11.15 |
| Completion time | The first test | 22.88 ± 2.96 | 23.55 ± 3.75 | 22.57 ± 3.64 |
| | The retest | 21.39 ± 3.51 | 18.71 ± 3.06 | 25.44 ± 5.01 |

## 2. Experiment 2: the role of sequence matching in the enhancing effect of declarative memory on procedural memory

The aim of Experiment 2 was to explore the role of sequence matching in the enhancing effect of declarative memory on procedural memory found in Experiment 1 on the basis of the semantic association between the two memory tasks. To achieve this, we compared the scores of two kinds of sequence matching conditions with that of the baseline group without the declarative task. If the performance of the sequence matching group was significantly superior to that of the sequence mismatched group as well as that of the baseline group, then we could conclude that sequence matching played a key role in the enhancing effect found in Experiment 1.

### *2.1. Method*

We used a single-factor between-groups design, and the independent variable was sequence matching (sequence matching, sequence mismatched and non-semantic word/baseline). Sequence matching means that the order of the words is consistent with the order of the actions.

#### *2.1.1. Participants*

Sixty students were randomly recruited. Participants (25 men, 35 women) were between the age of 18 and 25 years (mean = 20.5 years, SD = 3.50) and had a normal or corrected-to-normal vision. All participants had not participated in any action training or similar memory experiments before. All were paid for their participation. These participants were randomly divided into three groups, twenty in each group.

#### *2.1.2. Materials*

The material of procedural learning task was the same as that of Experiment 1. The material of declarative task was consistent with that of the semantic association group of Experiment 1, but difference existed in the presentation order of the sequence matching group and the sequence mismatched group. In the sequence matching group, the order of words was exactly the same as that in Experiment 1, but in the sequence mismatched group, the order of words was unordered and did not match the order in the word-list of Experiment 1. This means that words in the sequence matching group exactly match the representation concepts of actions (in the action learning task), and words in the sequence mismatched group do not match the representation concepts of actions (in the action learning task) at all.

#### *2.1.3. Procedure*

The procedure of Experiment 2 was the same as that of Experiment 1.

### *2.2. Results*

The first test and retest results of action sequence for the three subject groups are depicted in table 2. A one-way ANOVA was conducted on the accuracy and completion time of the first test for sequence matching. There were no significant difference across the three subject groups both in accuracy and completion time (for accuracy, $F_{(2,57)} = 1.14$, $p = .33$, $\eta_p^2 = 0.04$; for completion time, $F_{(2,57)} = 2.51$, $p = .09$, $\eta_p^2 = 0.08$) of the first recall of actions, indicating no significant difference in memory ability among the three groups that could account for differences on the experimental grouping variable.

A one-way ANOVA was conducted on the accuracy and completion time of the retest for sequence matching. For accuracy, this analysis yielded a significant main effect of sequence matching, $F_{(2,57)} = 8.239$, $p = .001$, $\eta_p^2 = 0.224$. Post hoc comparisons showed that the accuracy of the sequence matching group was significantly higher than that of the sequence mismatched group, $p = .001$, and it was also significantly higher than that of the baseline group, $p = .001$; there was no significant difference between the accuracy of the sequence mismatched group and that of the baseline group, $p = .850$. For completion time, the main effect of sequence matching was not significant, $F_{(2,57)} = 2.713$, $p = .075$, $\eta_p^2 = 0.087$. However, we wanted to know the difference between the sequence matching group and the sequence mismatched group, so we still did post hoc comparisons and found that the sequence matching group was significantly faster than the baseline group, $p = .028$, however, other comparisons were not significant (the sequence matching group compared with the sequence mismatched group, $p = .555$; the sequence mismatched group compared with the baseline group, $p = .104$).

### *2.3. Discussion*

The difference of the completion time of the sequence matching group and the sequence mismatched group was not significant. This may be related to the strength of semantic repetition priming of materials. Semantic priming refers to a preparing state that our cognitive system enters in for processing some words (stimulus) that semantically associated with the previous words (other stimulus) we learned before, and this preparing state plays a beneficial role in promoting subsequent processing activities. Individuals can respond more quickly when previously encoded content appears again in semantic form (Demb et al., 1995). In this study, there is semantic association (words are consistent with the representation concept of action) both in the sequence matching group and the mismatched group. When a word appears, it is equivalent to the restart of the semantic information of action. The strength of semantic association of the sequence matching group is equal to that of the sequence mismatched group due to the same materials, causing the same strength of semantic priming. This may result in no significant difference in completion time between the two groups.

In terms of accuracy and completion time, the difference between the sequence mismatched group and the baseline group was not significant. If semantic association doesn't have any effect on the performance of procedural memory (declarative memory can interfere with procedural memory in unrelated situations, see Gagné & Cohen, 2016), the sequence mismatched group should be worse than that of the baseline group. But it was not the case, the performance of the sequence mismatched group wasn't worse than that of the baseline group, indicating that semantic association is vital to the relationship between two tasks. That is to say, even if the order of the declarative sequence does not match that of the procedural sequence, the interference of declarative memory on procedural memory can still vanish as long as there is semantic association. These results further support the founding of Expriment 1 that semantic association can make the interference effect of declarative memory on procedural memory vanished alone.

**Table 2**
Mean and standard deviation (in parenthesis) for accuracy (%), and completion times (ms) for different sequence matching levels in Experiment 2.

| | | Baseline group | Sequence matching group | Sequence mismatched group |
|---|---|---|---|---|
| Accuracy | The first test | 80.50 ± 8.26 | 76.50 ± 10.40 | 77.00 ± 8.65 |
| | The retest | 81.50 ± 7.45 | 91.00 ± 8.52 | 82.00 ± 8.94 |
| Completion time | The first test | 21.67 ± 1.85 | 20.45 ± 4.93 | 22.78 ± 2.12 |
| | The retest | 19.84 ± 2.07 | 17.43 ± 4.85 | 18.07 ± 2.56 |

The results of the sequence mismatched group were not significantly better than those of the baseline group both in accuracy and completion time. When compared with the baseline group, however, the sequence matching group was significant better. This means that when words and actions match both semantically and sequentially, words can facilitate the retrieval of actions; when words and actions match semantically but not sequentially, however, the enhancing effect of words on actions can not be observed.

The results of Expriment 2 imply that sequence matching between two sequences is also a crucial retrieval clue and it is vital to the enhancing effect observed in Expriment 1. Semantic association between declarative memory task and procedural memory task can weaken the interference effect caused by the successive presentation of these two tasks to a non-existent level, but it can not reverse such interference effect to the enhancing effect. However, with sequence matching, an enhancing effect can be induced. This indicates that on the basis of semantic association, sequence matching can play a positive reinforcement role in the influence of declarative memory on procedural memory.

## 3. General discussion

Immediately after learning, new memories undergo an initial labile period (more than a few days) before being stabilized. During the labile period, newly acquired memories are sensitive to interference and trauma. There is considerable evidence that the stability of long-term memory is disturbed by certain treatments. For example, the application of TMS to M1 immediately after learning finger the action sequence can damage the memory of action sequence (Censor, Dimyan, & Cohen, 2010). Systemic drug injections or electric shocks given soon after action training can also block the stability of long-term memory, but the same treatments a few hours or days later have no such effect (cited from Nader, Schafe, & Ledoux, 2000). The stability of memory is closely related to protein synthesis (Dudai, 1996). RNA can be prevented from being translated into protein through drug manipulation, which therefore can destabilize memory. For example, injecting anisimycin, a protein synthesis inhibitor, into the LBA (a region involved in fear learning by lesion) shortly after action training can destroy the stability of fear memories (Schafe & LeDoux, 2000). These studies have shown that newly acquired memories are unstable. Due to instability, two newly acquired memories can be integrated and organized (McKenzie & Eichenbaum, 2011). In the study of the word-list memory, it also found that when two phrases were learned one after another, the items of the former phrase were involved in the recalling content of the latter phrase (e.g., Schult, von Stülpnagel, & Steffens, 2014). This means that the two newly acquired phrases can be integrated. It is this instability of memory that provides a window of opportunity for declarative memory to influence procedural memory.

Previous studies have reported that declarative memory can interfere with procedural memory (e.g., Brown & Robertson, 2007; Gagné & Cohen, 2016; Keisler & Shadmehr, 2010; Poldrack & Rodriguez, 2004). This interference effect was also verified in this study. Human functional brain imaging studies have shown that brain regions, such as MTL, can be activated during both declarative and procedural learning, suggesting an overlap between declarative and procedural learning (e.g., Poldrack et al., 2001). Competition for nerve resources in the sharing brain regions may lead to interference. In addition to verifying the interference effect, the present study also found that declarative memory can enhance procedural memory, and semantic association and sequence matching between the two tasks played different roles in the enhancing effect.

Association between items can affect the target memory. Heuer, Crawford, and Schubö (2017) presented a cue (pointed to one of the eight locations) during the interval between the presentation of the memory items and the test item to explore the effect of the cue on the target memory. In their study, the strength of association between the cue and the test target was different. As a result, the closer the cue was to the target, the better the performance of the target memory. Furthermore, semantic association between items can also ensure the effective completion of the target tasks. In a classic picture-word interference study, Rosinski (1977) found that words that appeared in the same vision field as pictures can affect picture-naming performance to varying degrees. When the semantic information of a word was highly consistent with the semantic information of the picture, the word can enhance the naming performance of the picture. However, when the strength of semantic association between the word and the picture was low or presenting a word without semantic information, the naming task can be inhibited. This indicates that semantic association plays an important role in regulating the performance of tasks involving two or more items. Similar results have been obtained in the current study. It found that semantic association can weaken the supposed interference effect of declarative memory on procedural memory. The spreading activation model of semantic processing (Collins & Loftus, 1975) holds that each concept in a conceptual network is a node, and a conceptual network is organized by semantic similarity or semantic association between concepts. When a concept is processed, the network nodes of the concept are activated, and then this activation spreads around the connection. The strength of spreading is affected by the strength of association between concepts. The closer the relationship between concepts, the easier it is to activate each other when recalling. Both words and actions have semantic information. In the case of high strength of semantic association, the semantic information of actions and words can be activated mutually. What's more, the highest strength of mutual activation can be achieved. When the word information is consistent with the semantic information of the action, it is equivalent to a kind of repeated activation. Accordingly, presenting actions and words that characterize actions successively is equivalent to repeating two actions (or two words that characterize actions). In this case, the presentation of words enables individuals to learn actions again. Sara (2000) believed that if the learned content was reminded by the same content after encoding, the susceptibility effect of memory can be observed, which was reflected in the enhanced performance of memory. This shows that re-training (or re-learning) can enhance memory.

However, there may be differences in the strength of re-training under different conditions, and not all types of re-training can take effect. In the influence of the word-list memory on the action sequence memory, semantic association alone can not make re-training effective—leading to an enhancing effect. Sequence matching may be indispensable for re-training to go into effect. Sequence plays an important role in sequence learning tasks. A growing number of studies have suggested that people can benefit from a repeating sequence even though they are not aware of it. For example, when the presentation of stimuli had followed a regular pattern in serial reaction time tasks, individuals' responses had tended to be faster (relative to random sequence conditions) even though they could not report potential patterns (e.g., Cohen et al., 1990; Curran & Keele, 1993; Nissen & Bullemer, 1987). In a learning task involving multiple sequences, when the first sequence appears, individuals tend to make an expectation that the order of the next sequence is the same as that of the first sequence. When all the subitems in the sequence are presented in a fixed order, individuals' expectations are valid (e. g., Downing, 1988). In the current study, similar results can be observed. In the case of a high semantic association between two sequence tasks, when the first word is presented in the word-list task, in order to reduce cognitive load, individuals may expect the order of items in the word-list to be consistent with that in the action sequence learned previously. But the effectiveness of this expectation is influenced by the actual situation. If the word-list matches the action sequence in sequence, then this expectation will be effective; conversely, if the word-list does not match the action sequence in sequence, then an invalid expectation can be observed. Under an effective expectation condition, the presentation of each word in the word-list can serve as a reminder of memory traces for the corresponding action (match word semantically and sequentially) in the action sequence, which guarantees a higher effectiveness of re-learning. As the susceptibility to action increases, individuals can ultimately be guided to recall these matching actions. On the contrary, under an invalid expectation condition, although semantic information in the word set is consistent with semantic information in the action set, each word does not match the action it represents in order. The presented word may not serve as a reminder of memory traces for the corresponding action (only match word semantically). In this case, the strength of re-training is so low that it is impossible to break the threshold for re-training to take effect.

In daily life, you always find that when you learn a series of actions, you can use semantic coding to master these actions faster. According to this, many people believe that the combination of semantics and action can promote the mastery of action. However, acquisiting motor skills is a more complicated process than what we think, we should not only focus on semantic association. This study indicates that in the influence of declarative memory on procedural memory, the generation of an enhancing effect is a hierarchical process. Relying only on semantic association is not enough for the generation of the enhancing effect, which also requires the participation of sequence matching. The semantic association between tasks is the necessary but insufficient condition for the enhancing effect between two memory systems, while both semantic association and sequence matching existing is the necessary and sufficient condition for its generation.

In conclusion, although there are great differences in brain structures between the declarative and procedural memory systems, they can be connected by the hippocampus. The current study reveals that newly acquired procedural memory is labile and susceptible to declarative memory. However, the impact of declarative memory on procedural memory is not a fixed relationship, it is modulated by semantic association and sequence matching (for sequence tasks) between two tasks. It is concretely embodied in the fact that performing declarative memory task and procedural memory task one after another, the former can interfere with the latter, but semantic association between them can vanish this interference. Further, sequence matching can play the role of co-reinforcement and induce declarative memory to facilitate procedural memory.

Although this study explores how semantic association and sequence matching regulate the effect of declarative memory tasks presented in the procedural skill coding stage on procedural memory, and some interesting results are obtained, it is not clear whether the impact of declarative memory on procedural memory can be still regulated by semantic association and sequence matching after a period of consolidation of procedural memory. To help us better understand the interaction between procedural and declarative memory, further research is needed to clarify this.

## Conflicts of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Declarative memory affects procedural memory: The role of semantic association and sequence matching”.

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