Working Memory and Education: Recent Advances in Cognitive Psychology

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Working memory underpins the transient retention of information in the service of cognitive processes within a variety of tasks. As this memory function restricts our ability to regulate mental processes, it potentially characterizes our learning and educational activities. This article reviews three lines of working memory research in cognitive psychology : Short-term retention of verbal information, the relationship between storage and processing in working memory, and the role of working memory in learning activities. These three research areas constitute promising directions in working memory research. Although the present paper limited its scope to relatively basic studies, the findings reported here could lay the foundation for applied working memory research in educational settings.

Key Words : Working memory, Short-term memory, Attentional control, Long-term knowledge, Learning

Introduction

Working memory (WM) is a set of functions that support the temporal storage of information in the service of higher cognitive processes such as reading, reasoning, and mental arithmetic (e.g., Baddeley, 2012). A related term, WM capacity, has been defined as the maximum amount of information that an individual can hold at one time during the process of performing a given task. WM capacity is assumed to restrict our ability to process information in everyday life (Conway, Jarrold, Kane, Miyake, & Towse, 2007). Thus, this key concept likely characterizes our learning and educational activities (e.g., Miyake et al., 2010).

This study reviews recent research on the relationship between WM and learning and education, examining three major contemporary topics in cognitive psychology. The first topic targets the mechanisms of short-term information retention and concerns the type and nature of information retained. This issue is particularly important when attempting to explain the mechanisms of vocabulary acquisition, the process for forming long-term knowledge of new vocabulary. The second topic concerns the relationship between information storage and processing, a fundamental issue in WM, with a particular focus on recent developments in research on WM span tasks. The third topic concerns domain-general WM functions in learning activities. Finally, the study suggests future directions of WM research in cognitive psychology.

Short-term retention of verbal information

Working memory, short-term memory, and long-term knowledge

Short-term memory is a concept that describes the performance of a memory task that requires retention of information for a short period of time. Thus, short-term memory function is assumed to differ from WM. However, both functions are supported by temporary information retention systems. Therefore, they can be seen as having the same basic structure, yet each appears to work differently depending on the situation (Saito & Miyake, in press). Alternatively, one can consider short-term memory a storage unit that serves as a component of WM. For example, the phonological loop

of Baddeley's WM model (Baddeley, 2012) is a system that explains the phonological characteristics of verbal short-term memory within the theoretical framework of WM.

Short-term memory for verbal material constitutes the foundation for vocabulary acquisition because it can be achieved by temporary retention of the phonological form of new vocabulary (Baddeley, Gathercole, & Papagno, 1998 ; Gathercole, 2006 ; but see, Melby-Lervåg et al., 2012). In addition, substantial evidence demonstrates the contribution of long-term knowledge to short-term retention of phonological sequences assessed by short-term memory tasks (Gupta & Tisdale, 2009). For example, children's performance on a nonword repetition task (repeating a meaningless series of speech sounds that do not form real words, such as, "de-so" in Japanese) is better for nonwords with a highly familiar sound sequence in their first language than for those with an unfamiliar sound sequence (Yuzawa & Saito, 2006 ; Yuzawa, Saito, Gathercole, Yuzawa, & Sekiguchi, 2011). Furthermore, research has found that short-term memory performance is better for verbal material from a familiar language (i.e., the individual's first language) than an unfamiliar one. This is called the language-familiarity effect (e.g., French & O'Brien, 2008 ; Sakuma & Saito, 2012). Recent studies have further established that learners' phonological knowledge in their first language strongly affects their segmentation of foreign language phonology in short-term memory tasks (Minaguchi, Yuzawa, & Li, 2013 ; Yuzawa, Yuzawa, Sekiguchi, & Li, 2012).

Although the presence of this reciprocal relationship between verbal short-term memory and long-term knowledge has generally been accepted during the last two decades, the operation of the links between them remains unclear (Thorn, Frankish, & Gathercole, 2009). One of the most promising approaches to this question might be to scrutinize verbal short-term memory systems in the context of language processing systems.

Verbal short-term memory and language processing

Since the 1960s, research has reported evidence suggesting a close relationship between verbal short-term memory and language processing (Baddeley, 2003 ; Jacquemot & Scott, 2006). The phonological loop model provides a framework for the relationship between short-term memory and language processing. The phonological loop consists of two components that perform the storage and activation of phonological information (Baddeley, 2012). When individuals memorize a series of visually presented characters, they first activate phonological information from the stimuli and serially store this phonological information. This information soon becomes unavailable because of interference or decay. For this information to be retained, it must be reactivated promptly before it is completely lost. The interaction between storage and reactivation is a process called rehearsal, which supports the performance of verbal short-term memory tasks. The storage component is called the phonological store, and the activation component is called the articulatory control process. The former is strongly related to the process that supports language perception, whereas the latter supports language production (Saito & Baddeley, 2004). One might assume that the functioning of the phonological loop emerges from interactions between speech perception and production systems (Majerus (2013) provides a recent review of this issue).

Memory for serial order

It is imperative to note that the key function of the phonological loop is the temporary retention of the serial order of memory events. The essence of verbal information is found in its seriality ; temporary retention of serial order enables the processing of verbal information. Accordingly, a serial recall task with verbal material (words or digits) is often used to measure verbal short-term memory ability. During this type of task, participants are asked to memorize several words or digits presented sequentially, and report the order of the presented items. A nonword repetition task can be used to measure children's verbal short-term memory (see *Working memory, short-term memory, and long-term knowledge* in the present paper). This task measures the ability to repeat the sound sequence of a novel word

(Gathercole, 2006).

Although the original phonological loop model emphasized the importance of the retention of serial order information, it did not precisely explain the process by which serial order information is retained. Research on this process has progressed by exploring the mechanisms that are common to both verbal short-term memory and language processing (e.g., Acheson & MacDonald, 2009 ; Page, Madge, Cumming, & Norris, 2007 ; Saito & Baddeley, 2004). In addition, recently developed computer simulation models provide conceptual architectures of the cognitive system that serve as a model for the retention of serial order information. These models also enable a substantive, robust examination of the retention mechanism(s) for serial order information, including relationships with long-term memory (Burgess & Hitch, 2005 ; Page & Norris, 2009). Although previous studies examined mechanisms of serial order memory largely in the verbal and phonological domain, empirical and theoretical developments in this area have suggested the presence of common principles for serial order memory in different domains (e.g., Hurlstone, Hitch, & Baddeley, in press).

The nature of information retained

Advances in this field thus far have shown that various types of knowledge and information support the temporary storage of verbal information. For example, Ueno and Saito (2013) demonstrated that short-term retention of spoken words could be supported by internally generated visual representations derived from the spoken words. Although they suggested that the role of such visual representations is likely minimal in the retention of serial order, the paired association of two words (specifically, the retention of four pairs of words in a list) largely benefited from the presence of such visual representations. Note that some researchers assume that paired associative memory and serial order memory are based on the same mechanisms (e.g., Farrell, 2012). Logie, Della Sala, Wynn, and Baddeley (2000) demonstrated that serial order recall of a visually presented list of words is influenced by the visual

similarity within the list. Immediate serial recall of a set of words that are visually similar (e.g., FLY, PLY, CRY, DRY, TRY, SHY) is worse than for a series of words that are visually dissimilar (e.g., GUY, THAI, SIGH, LIE, PI, RYE). In addition, a study that used kanji characters in Japanese as memory stimuli (Saito, Logie, Morita, & Law, 2008) reported that when the retention of serial order information was evaluated after the visual and phonological similarity of the stimuli were manipulated in the same experiment, two similarity effects were simultaneously observed : worse recall for a sequence with higher similarity. These results suggest that not only phonological information but also visual information contributes to the retention of serial order information for verbal material. A recent study, however, suggested that orthography, but not visual information, might influence the results (Furstenberg, Rummer, & Schweppe, 2013).

Lexical and/or semantic knowledge is known to influence performance on verbal short-term memory tasks. For example, participants perform better with serial recall of real words than nonwords (See, Stuart & Hulme, 2009 for a review). When using real words, individuals perform better on words with high imageability or concreteness (i.e., rich in semantic information) than words with low imageability or concreteness (Walker & Hulme, 1999 ; Jefferies, Frankish, & Lambon Ralph, 2006 ; Ueno, Saito, Saito, Tanida, Patterson, & Lambon Ralph, 2014).

The view that semantic information underpins the retention of phonological information has been supported by neuropsychological studies. Semantic dementia is a progressive disease leading to the loss of semantic knowledge due to degeneration of the anterior temporal lobe. Although the loss of semantic knowledge leads to various clinical symptoms (Patterson et al., 2006), these individuals do not exhibit difficulty with phonological processing as measured by phonological discrimination tasks, which suggests that semantic dementia is a form of selective impairment of semantic memory. It has been reported, however, that an individual with semantic dementia would demonstrate phonological errors (such as saying "rint and mug" for "mint and rug")

when recalling several words that are orally presented. This shows that loss of semantic knowledge influences the temporary retention of phonological information, and further that semantic knowledge plays an important role in the retention of the phoneme sequence of a word. In the preceding example, it is assumed that the meaning of the word "mint" connects the phonemes (e.g., /m/) into the word mint. This concept that semantic knowledge binds phonemes together is called the semantic binding hypothesis (Patterson et al., 1994). This hypothesis is supported by behavioral data from healthy adults (Jefferies et al., 2006), neuropsychological data from semantic dementia patients (e. g., Hoffman et al., 2009), and simulation data from computational modeling (e.g., Ueno et al., 2014, based on the architecture provided by Ueno, Saito, Rogers, & Lambon Ralph, 2011).

Note that the influence of lexical/semantic knowledge is greater on the retention of item information than on the retention of serial order information (e.g., Walker & Hulme, 1999). At the same time, the retention of item information is in fact measured by the retention of a phoneme sequence within an item. The semantic binding hypothesis suggests that if the item is an actual word, the retention of a phoneme sequence within an item is not an issue because the binding of a phoneme series is sufficiently powerful. However, when contributions from lexical/semantic long-term memory are weak (e.g., when a healthy individual is recalling nonwords, Jefferies et al., 2006, or an individual with semantic dementia is recalling real words, Hoffman et al., 2009), the retention of a phoneme sequence within an item is compromised, and the likelihood of errors within the phoneme sequence increases. When an error occurs in such a situation, it is considered an item error. Thus, a given proportion of item errors might originate from the retention of serial order information within an item, suggesting a substantial influence of serial order memory on the retention of verbal material.

The relationship between storage and processing in working memory

Working memory span

A WM span task is known as a complex span task ; as the name implies, it comprises a combination of storage tasks and processing tasks. Although several WM span tasks exist, the most widely used in Japan is the reading span test (Endo & Osaka, 2012). In this task, several sentences are presented sequentially, and participants are asked to read the sentences aloud and memorize the last word in the sentence (in the Japanese version, the words that are underlined). Thus, participants must be engaged in both components : Reading the sentences aloud and word retention. Performance on this task is evaluated not by language processing measures such as reading comprehension or speed, but by recall of the memorized words (Friedman & Miyake 2004 ; 2005 provide details of the implementation method and scoring). Overall, it is assumed that the reading span test measures WM function in reading. A relatively high correlation between reading span scores and reading ability test scores has been observed in support of this assumption (Daneman & Merikle, 1996). Other WM span tasks include counting span (e.g., Towse, Hitch, & Hutton, 1998), operation span (e.g., Kobayashi & Okubo, 2014), spatial span (e.g., Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001), picture span (Tanabe & Osaka, 2009), and reasoning span (Saito, Jarrold, & Riby, 2009). Each consists of both storage and processing components.

Effects of processing on storage

The difference between the WM span task and conventional short-term memory tasks is the processing component found in the former. Consequently, analyzing the influence of the processing component on storage is thought to be the key to a holistic understanding of WM. In fact, there are several factors that could be influenced by the processing component and, in turn, affect the storage component. For example, the processing component could increase the length of delay between item encoding and recall (Saito et al., 2009 ; Towse et al.,

1998), increase the amount of information processing before recall (Maehara & Saito, 2007 ; Oberauer & Lewandowsky, 2013 ; Saito & Miyake, 2004), and affect the degree of cognitive load, defined as the proportion of time spent for actual processing during the processing period (Barrouillet & Camos, 2012). Each of these factors potentially contributes to storage performance in WM tasks.

In an experiment reported by Maehara and Saito (2007), words (i.e., verbal material) were used as memory items for the WM task, and a sentence judgment task was added (for example, asking whether the statement, "The earth is a cube," is true or false) before each memory item was presented. Results demonstrated that memory performance was better when only one sentence judgment task was inserted between the final and penultimate words than when three sentence judgment tasks were inserted. When more processing occurs during the final processing period, there is more interference with the words that have been retained until that moment. It is believe that this interference leads to diminished memory performance. The interference effect was tested in another condition that used the same processing task (sentence judgment), but the positions of dots within a matrix (i.e., visuospatial information) were used as memory items. In this case, the number of sentence judgment tasks inserted before the last memory item had no effect. In short, when the memory stimuli and processing stimuli come from different domains (in this case, verbal and visuospatial), there is no effect of processing load on storage. This outcome suggests that the influence of processing on storage is, at least in part, domain-specific.

Effects of storage on processing

As mentioned, several WM studies have examined the memory function itself, primarily investigating the influence of processing on storage. However, during actual learning, the influence of both processing on storage and storage on processing are important ; several early studies conducted analyses from this perspective (e.g., Hitch & Baddeley, 1976). A few recent studies have also reported on the influence of storage on processing as an effect of

memory load within a WM span list. For example, Maehara and Saito (2007) compared the response times for the first processing element within a list (a sentence judgment task) with those for the final processing element. The first element is not influenced by memory load, as it occurs before the presentation of memory items. This is not the case for the final element, which only appears after the participant has retained the remainder of items in the list. Thus, memory load is expected to influence processing. This experiment demonstrated that response times were longer for the final processing item than for the first, but there was no difference in the judgment's accuracy. This memory load effect was obtained both when memory items were words and spatial dot positions. That is, regardless of stimuli characteristics (verbal or visuospatial), an increase in the volume of memory information decreased the speed of concurrent processing.

The influence of storage on processing is typically observed in response times rather than accuracy (e. g., Hitch & Baddeley, 1976). It would seem reasonable that the number of processing errors would increase when memory is constrained and information necessary for processing is lost because of memory load ; however, this is not the case. Evidently, there is still much to be explored concerning the mechanism(s) related to the deterioration of processing time while producing correct answers. The time-based resource sharing model or TBRS model (Barrouillet, Portrat, & Camos, 2011) offers a promising solution.

The TBRS model, which provides an explanation for WM span task performance, is based on the following assumptions (Barrouillet & Camos, 2012). Processing and storage in WM are supported by a single limited capacity referred to as attention. Here, representations related to the memory items are immediately exposed to temporal decay as soon as attention is shifted from those representations. As both processing and storage are controlled cognitive activities that require attention, they cannot occur simultaneously. That is, processing and storage are temporally mutually exclusive processes, and only one or the other can occur at any given

time.

The TBRS model stipulates that memory items, having been encoded and exposed to temporal decay due to processing that diverts attention, can be reactivated by shifting attention back to the memory items before they are completely forgotten. This reactivation (retention activity called refreshing) can be performed between processing activities, even during the processing period ; recall performance is then determined by the proportion of the processing period (i.e., the retention period) that can be used for reactivation (i.e., the amount of time attention is shifted to storage activities during the entire processing period). In this model, the proportion of time during which attention is shifted to processing is defined as cognitive load (CL), and a formula for the relationship between CL and recall performance is proposed. In this regard, Barrouillet et al. (2011) proposed a model placing short-term memory and WM on a continuum, assuming that situations in which no CL is necessary constitute short-term memory task situations.

According to the TBRS model, reactivation of memory items (i.e., refreshing) can occur during the processing period in WM span tasks. Refreshing inevitably interrupts processing activities during the processing period. Consequently, the larger the number of memory items to be retained, the longer the period of interruption by refreshing during the processing period becomes. As the period during which processing is interrupted expands, the amount of time necessary for processing apparently increases (Vergauwe, Camos, & Barrouillet, in press). It is further suggested that the resources necessary for refreshing are domain-general, which is consistent with the domain-generality of memory load effects shown in Maehara and Saito (2007).

Domain-general control functions

Several WM models propose domain general (i.e., capable of processing all types of information) control mechanisms similar to the TBRS model. Baddeley's well-known multi-component model has a domain-general central executive in addition to domain-specific retention subsystems (Baddeley,

2012). With regard to domain generality, the same can be said of Engle and colleagues' model centered on controlled attention (Engle, 2002) and Cowan's model (Cowan, 2005). These models differ in the suggested mechanisms of domain-general control, such as whether it is a single entity (e.g., Barrouillet & Camos, 2012) or composed of several control functions (Baddeley, 2012). Nevertheless, research on WM as a whole tends to emphasize domain-general control mechanisms, and it would be difficult to explain related phenomena without assuming the presence of such functions.

The role of working memory in learning activities

Working memory and task goal maintenance

Any learning activity requires the learner to concentrate on the task and to maintain attention on task-relevant information. To achieve this function, the learners must retain the task goal and control their attention in reference to the goal. Retention of the task goal is essential for executing any purposeful action (e.g., Duncan, 2013), and task goal maintenance is an important function of WM (Saito & Miyake, in press). It is thought that deficiencies in task goal maintenance and attentional control supported by such goal information constitute one factor that causes task-unrelated thought, as detailed in the next two sections.

Working memory and mind wandering

The phenomenon that describes an inability to concentrate on a task during a learning activity is called task-unrelated thought or mind wandering. It is assumed that this phenomenon is related to WM functioning.

For example, McVay and Kane (2012) suggest that the relationship between WM span task performance and reading comprehension can be mediated by task-unrelated thought. Their participants performed three WM tasks, seven reading comprehension tasks, and three attentional control tasks. Using an experience sampling method, they also investigated whether task-unrelated thought was generated during some of the reading comprehen-

sion and attentional control tasks. Experience sampling methods were used by Kane et al. (2007) to examine task-unrelated thought in everyday life. Specifically, when participants were engaged in an activity, the experimenter randomly asked what they were thinking at that time. McVay and Kane asked these questions during the performance of attentional control and reading comprehension tasks. When the participant was thinking about the past or the future, rather than the current task, they assumed that task-unrelated thought was present. McVay and Kane also found that the frequency of task-unrelated thought was lower for an individual with better WM task performance. It was further demonstrated that a correlation between WM task performance and reading comprehension performance was partially mediated by task-unrelated thought, which suggests that WM capacity might be related to an ability to control thought. That is, deficiencies in WM functioning, which supports task-goal maintenance, trigger task-unrelated thought, which in turn leads to diminished reading comprehension performance (Kane & McVay, 2012).

Mind wandering and learning activities

The influence of task-unrelated thought on cognitive activity as described above has been found to influence classroom learning activities (Szpunar, Moulton, & Schacter, 2013b). For example, using filmed university lectures, Risko, Anderson, Sarwal, Engelhart, and Kingstone (2012) presented questions to evaluate task-unrelated thought at five, twenty-five, forty, and fifty-five minutes after the lecture began. The frequency of task-unrelated thought was higher and memory of lecture material was worse during the second half of the lecture. This type of relationship between task-unrelated thought and memory of lecture material was also found in an inter-individual differences analysis. Specifically, individuals who reported several task-unrelated thoughts recalled less lecture content. Furthermore, a recent intervention study revealed that inserting memory tests during lectures reduced the frequency of task-unrelated thought and consequently improved memory of the lectures (Szpunar, Khan, & Schacter, 2013a).

Working memory and task set

Previous sections of this paper outlined the importance of task goal maintenance in learning activities and its support by WM. The role of task goal maintenance focuses on, but is not limited to, maintaining attention on information related to the task. Let us consider an experimental situation as an example. During the Stroop task (Meier & Kane, 2013), color words such as "red" and "blue" are visually presented to participants. These words are presented in colored ink. Sometimes the words match the ink color, and sometimes they do not. Participants are typically asked to name the color (not to read the word) ; when the ink color does not match the word, response times and errors increase. This is referred to as the Stroop effect. This phenomenon is caused by interference from the color word because reading a color word is a more habitual and natural response than naming an ink color (Miller & Cohen, 2001). In addition, when the task goal of "naming the color of the ink" becomes unavailable, even temporarily, the participant tends to commit the error of reading the word. This phenomenon is called goal neglect (Duncan et al., 2008).

In a condition in which the task goal is available, we prepare ourselves so that our cognitive processing will function efficiently to achieve the task goal. This preparation is called a task set and can be considered an "attitude" toward the task. We control our attention to focus on the ink color rather than the word information. We then utter the color name while inhibiting the interfering word information. For this series of processes to proceed smoothly, one must prepare the cognitive system, even before the stimuli are presented. In this case, participants prepare for both resolving the competition between word and color and identifying the information particular to the task. For example, the color name is used in the response, not digits or other words. Therefore, only color names are prepared as choices for a response. In other words, to perform the Stroop task successfully, focusing on

the color stimuli presented is insufficient ; the entire series of processes must be prepared for a participant to succeed. The existence of a task set has been demonstrated in research on task switching, and executive function is considered to be involved in this process (Monsell, 2003).

Task goal maintenance supported by WM is useful for building a task set for the task in question. For advance research investigating the role of WM in the classroom, it will be increasingly important to examine the ways in which the construction, maintenance, and performance of such a task set work toward actual learning. A promising approach to this issue might be to postulate the presence of procedural working memory (Oberauer, 2009), a structure that can retrieve and retain plans for action.

Summary and future directions

Diversity of representations in working memory

This study first reviewed recent developments in research on temporary retention of verbal information. This work has shown that lexical/semantic information as well as phonological information are involved in verbal short-term memory in addition to the fact that visuospatial (or orthographical) information is involved in the temporary retention of verbal information. When examining verbal short-term memory, we must consider the collaborative role of these types of information. One question here is how these types of information are functionally (Baddeley, Allen, & Hitch, 2011) and computationally (Rogers et al., 2004) integrated into single representations. The scrutiny of the organization of diverse representations will further advance our understanding of how these representations operate in our learning and educational activities (see below).

Domain-specific working memory

Within any processing task, short-term retention of information is hindered by processing, and this interference is thought to be partly domain-specific, as demonstrated by Maehara and Saito (2007). This phenomenon could be considered empirical evidence of the modality effect (Moreno & Park, 2010) within the

cognitive load theory used in classroom teaching–learning situations. The modality effect described here occurs when several interrelated pieces of information are presented simultaneously. In this situation, using two modalities (e.g., visual and auditory presentation) allows the use of two independent WM subsystems (Baddeley, 2012). Thus, the WM capacity available for learning increases as compared to a situation using a single modality (e.g., visual and character presentation).

Although the preceding example indicates the advantage of multiple-component domain-specific WM systems, research has also found that, in some cases, the presence of redundant information from multiple sources impairs learning efficiency, depending on the learners' experience (Artino, 2008 provides a review). Thus, it is again important to examine precisely how different types of information are integrated into single representations.

Domain-general working memory

It has also been demonstrated that processing activities are exposed to memory load, and that the influence of such memory load relates to domain-general attentional control (Vergauwe et al., in press). This type of domain-general attentional control is equivalent to aspects of controlled attention supported by Engle (2002), who assumed that it is indeed the fundamental function of WM. In fact, retention of the task goal, building a task set, and task-unrelated thought are all involved in domain-general attentional control. However, it is important to note that under certain circumstances, retention of a task goal (Saeki, Baddeley, Hitch, & Saito, 2013), building a task set (Miyake et al., 2004), and task-unrelated thought (Beilock et al., 2007) are concerned with WM specific to the verbal domain. Thus, future research should explore the role of domain-specific WM functions in domain-general control.

Conclusion

Research indicates that WM function and WM capacity are of critical importance for daily life, including various educational settings. Thus, researchers in psychology have become increasingly

interested in WM. Consequently, a substantial amount of literature has accumulated over the last few years that could not be fully addressed in this review. For example, the development of WM and its relationship to executive functions (Munakata, Snyder, & Chatham, 2012 ; Zelazo & Carlson, 2012), the roles of WM in social contexts (Lin, Keysar, & Epley, 2010 ; Maehara & Saito, 2011 ; 2013), and WM training (Chooi & Thompson, 2012 ; Harrison, et al., 2013 ; Melby-Lervåg & Hulme, 2013 ; Shipstead, Redick, & Engle, 2012) are very active, related research areas in cognitive psychology, but have not been discussed herein. Although the present paper focused on basic WM research, the findings reported could serve as an important tool for researchers seeking to expand upon these interconnected regions of WM research.

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