An Exploration of the Relations
Between External Representations and Working Memory

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Running Head: External Representations

ABSTRACT

It is commonly assumed that external representations aid working memory. However, very few studies have directly and explicitly examined just how external representations aid working memory, if they aid it at all. The current study extends Baddeley's original working memory framework to address the relation between external representations and working memory. The result is a framework of distributed working memory, which consists of an internal working memory, an external working memory, and a central executive. Three experiments are designed to examine the relation between internal and external working memory. The experimental results show that external working memory can hinder as well as enhance task performance. In other words, external representations do not always aid working memory. It is shown that the critical factor that determines task difficulty is the retrieval of information from internal and external working memory. Different representations across internal and external working memory and different encodings in internal working memory elicit different retrieval strategies, which give rise to different difficulty levels. It is argued that different patterns of behavior result from a constraint satisfaction process that minimizes the load of internal working memory and meanwhile satisfies the constraints set up by specific representations.

Working memory plays important roles in complex cognitive tasks that involve short-term storage and processing of information. Working memory is limited in its space of temporal storage, resources of attention, and amount of concurrent processing. Despite of such limitations, people can perform complex cognitive tasks fairly well when they interact with external representations, such as multi-digit multiplication with paper and pencil. One common assumption is that external representations serve as memory aids, that is, expand the limited capacity of working memory. Indeed, many cognitive activities such as problem solving, reasoning, and decision making can be successfully accounted for by models that assume a limited-capacity working memory along with a large capacity external memory (e.g., Atwood, Masson, & Polson, 1980; Johnson, Zhang, & Wang, 1994; Larkin, 1989; Newell & Simon, 1972; Payne, 1976). Studies of external representations have also shown that in many cognitive tasks, the more information in external representations, the easier the task (e.g., Zhang, 1996, 1997; Zhang & Norman, 1994, 1995). The memory aid hypothesis of external representations seems so trivial that it is often taken for granted. As a result, there has been very little empirical research that directly and explicitly examines just how external representations aid working memory, if they aid it at all. This article examines this memory aid hypothesis.

The working memory framework developed by Baddeley and his colleagues consists of three components: a central executive and two slave systems (Baddeley & Hitch, 1974; Baddeley, 1986, 1992). The central executive is assumed to be an attentional-controlling system that coordinates information from two or more slave systems or information resources. One slave system, the articulatory loop, stores and rehearses speech-based information. A second slave system, the visuo-spatial scratch pad (VSSP), stores and manipulates visuo-spatial information. The VSSP can be further decomposed into a visual and a spatial sub-component which are functionally independent (Baddeley, Grant, Wight, & Thomson, 1975; Baddeley & Lieberman, 1980; Logie, 1986; 1995; Logie, Zucco, & Baddeley, 1990).

Baddeley's working memory framework has been very successful in explaining a large body of working memory phenomena. However, it does not directly and explicitly address the relation between external representations and working memory. The objective of this article is to extend the original working memory framework to address this relation. The result is a framework of *distributed working memory* (DWM), which is shown in Figure 1. The original working memory is one of the two components of DWM: it is the *internal working memory* (IWM) that is based on internal representations and memorial processes. The second component of DWM is the *external working memory* (EWM) that is based on external representations and perceptual processes. IWM and EWM together form DWM, which is the actual working space of cognitive tasks that involve external representations.

IWM consists of the articulatory loop and VSSP of Baddeley's original framework. The contents in IWM have to be continuously rehearsed or refreshed in order to be maintained. The information in IWM is processed by memorial processes, such as the retrieval of a specific item from the articulatory loop or the retrieval of a specific position from VSSP. EWM is the external representation that is currently available to perceptual systems. The contents in EWM need not be maintained by effortful mental processes: they simply stay there[1]. The information in EWM is processed by perceptual processes, such as the search of the position of a specific object or the identification of the object at a specific position. The central executive, in addition to the attentional control processes assumed in the original framework, now also coordinates perceptual and cognitive processes, allocate attentional resources between IWM and EWM, and integrate the information from IWM and EWM.

In the present study, we design three experiments to examine the relation between IWM and EWM. In each experiment, we manipulate the distribution of information across IWM and EWM and the encoding of information in IWM. We show that EWM does not always aid IWM: it can hinder task performance as well. We argue that the critical factor that determines task difficulty is the retrieval of information from IWM and EWM. The implications of the experimental results will be discussed with respect to the general issues of external representations and working memory.

Insert Figure 1 about here

Overview of Experiments

The experimental task of the present study is based on the list-processing task originally used by Weber, Burt, and Noll (1986) and later modified by Dark (1990) and Carlson, Wenger, and Sullivan (1993; see also Wenger & Carlson, 1995). In terms of our current terminology of internal and external working memory, the original list-processing task can be described as an information retrieval task that requires subjects to alternately retrieve and report items from two information sources, which could be both internal, both external, or one internal and one external. For example, if the list B-F-C is in IWM and the list M-L-G is in EWM, then subjects are required to produce the sequence B-M-F-L-C-G by alternating between IWM and EWM to retrieve the letters. The first study using this task by Weber, Burt, and Noll (1986) showed that tasks with both IWM and EWM were more time-consuming and error-prone than those with only IWM and those with only EWM. The authors attributed this result to the extra cost of switching attention across IWM and EWM. However, a later study by Dark (1990), after controlling the task requirement that was not controlled in the study by Weber et al., indicated that the difficulty factor for the list-processing task was not the switching of attention across IWM and EWM, but the retrieval of information from IWM. The study by Carlson, Wenger, and Sullivan (1993; see also Wenger & Carlson, 1995) showed that the critical factor in the list-processing task was the coordination of activities, which depended on the means available for storing and generating sequences.

The studies mentioned above were designed to examine attention switching across IWM and EWM, not to examine the memory aid property of external representations. In the present study, we modify the original list-processing task to an information integration task, which requires subjects to integrate information from two sources to make decisions. More specifically, it is a sequential number comparison task based on two columns of digits. Subejcts are required to compare the corresponding digits in two target columns, one pair by one pair, to decide which digit in a pair was larger in magnitude. The task is shown in Figure 2. Each trial has two displays. Display 1 has two columns of digits with two or three digits in each column. The subjects are instructed to memorize these two columns of digits. After Display 1 disappears, Display 2 is presented at the same location and stays visible on the screen until all responses are made. Display 2 has two columns of digits and/or X's. Depending on how many columns are X's on Display 2, the two target columns can be both from Display 1, both from Display 2, or one from Display 1 and the other from Display 2. If Display 2 has two columns of digits (no X's), the task is to compare the two columns on Display 2. This condition is shown in Figure 2 as the *EWM-EWM* condition because the two target columns are both in EWM. If Display 2 has one column of digits and one column of X's, the task is to compare the column of digits on Display 2 with the column of digits on Display 1 corresponding to the column of X's of Display 2. This is shown in Figure 2 as the *EWM-IWM* condition because one target column is in EWM (Display 2) and the other is in IWM (Display 1). If Display 2 has two columns of X's, the task is to compare the two columns on Display 1. This is shown in Figure 2 as the *IWM-IWM* condition because the two target columns are in IWM. Subjects are required to make comparisons from the top to the bottom pair (row) as soon as Display 2 appears, by pressing the left key if the left digit is larger and the right key if the right digit is larger.

Insert Figure 2 about here

To successfully perform the sequential comparison task, subjects need to know the to-be-compared digits and their positions, which are represented differently in EWM and IWM. In EWM, the digits and their positions are simply the visual and spatial properties of the external representations. Retrieving a digit at a specific position from EWM is accomplished by perceptual processes that move eyes or attention to the digit at the specific position. In IWM, the digits are maintained in the articulatory loop and their positions are represented in VSSP. Retrieving a digit at a specific position from IWM is accomplished by memorial processes that rehearse through the digits in the articulatory loop and associate them with the positions in VSSP.

The digits in IWM can be encoded in different ways through different memorization procedures. Different encodings in IWM can affect how the digits in IWM are retrieved. By manipulating the distribution of information across IWM and EWM and the encodings in IWM, we designed three experiments. All three experiments used the same three representation types (*EWM-EWM, EWM-IWM, IWM-IWM*) shown in Figure 2, each of which could have either two or three digits per column. However, the encodings of digits in IWM were different for different experiments, resulting from different instructions for memorizing the digits on Display 1. In Experiment 1, subjects were instructed to memorize the digits on Display 1 *column by column*, that is, from the top to the bottom digit on the left column, then from the top to the bottom digit on the right column. In Experiment 2, subjects were instructed to memorize the digits on Display 1 *column by column in a reversed order*, that is, from the bottom to the top digit on the left column, then from the bottom to the top digit on the right column In Experiment 3, subjects were instructed to memorize the digits on Display 1 *row by row*, that is, memorize the top row first (from left to right), then middle row (if there is one) and bottom row. In all three experiments, however, the response patterns that subjects needed to make were always the same, that is, always from the top to the bottom pair (row).

These three experiments were designed to examine the following issues about IWM and EWM. The first issue is whether a task always becomes easier when more information is in EWM and less information is in IWM, that is, from hardest to easiest, *IWM-IWM* > *EWM-IWM* > *EWM-EWM*, regardless of how the digits are encoded in IWM. The second issue is whether the strategies for comparisons depend on representation types and encodings in IWM. In some cases, subjects may adopt a step-by-step strategy in which in which they make a single response after each pair of digits are compared. In other cases, however, subjects may adopt an end-of-sequence strategy in which they make all the responses at the end of sequence after all pairs of digits have been compared. The third issue is whether the strategies of retrieving digits are different between EWM and IWM and between different encodings of IWM. In some cases, to retrieve the two target digits for each comparison, subjects may adopt a pair-by-pair shifting strategy in which only the two target digits are searched or scanned for each comparison. In other cases, however, subjects may adopt an exhaustive strategy in which they have to go through the whole set of digits for each comparison every time even if not all the digits are needed for the comparison. The fourth issue is whether the capacity of the central executive is reduced with increased load in IWM. The fifth issue is what factors determine task difficulties. There are three possible difficulty factors, one or more of which can attribute to the difficulty of a task: (1) perceptual retrieval processes for EWM and the memorial retrieval processes for IWM might be different; (2) the strategies for comparisons might be different for different representations; and (3) the strategies for the retrieval of digits might be different for different representations. With an understanding of these issues, we can achieve a better understanding of the nature of EWM and the relation between EWM and IWM, and we can specify the details of the DWM framework at a deeper level.

Experiment 1

All three experiments of the present study used the same stimuli shown in Figure 2. However, the encodings of digits in IWM were different, resulting from different instructions for memorizing the digits on Display 1. In Experiment 1, subjects were instructed to memorize the digits on Display 1 *column by column*, that is, from the top to the bottom digit on the left column, then from the top to the bottom digit on the right column.

Method

Subjects. The subjects were 24 undergraduate students in introductory psychology courses at The Ohio State University who participated in the experiment for course credit.

Stimuli and Procedure. The stimuli are shown in Figure 2. They were presented on Macintosh computers. Subjects were seated about 50 cm from the computer monitors. The digits and X's were in 24 point New York font, with a horizontal inter-digit distance of 2.5 cm and a vertical inter-digit distance of 1.0 cm. Each trial consisted of two displays, preceded by a '+' sign for 500 ms for fixation. Display 1 had two columns of digits with two or three digits in each column, being presented for two seconds for cases with two digits per column and three seconds for cases with three digits per column (i.e., 500 ms per digit). The subjects were instructed to memorize these two columns of digits *column by column*, that is, memorize the left column first from the top digit to the bottom digit, then memorize the right column from the top digit to the bottom digit. One second after Display 1 disappeared, Display 2 was presented at the same location and stayed visible on the screen until all responses were made or until it was over ten seconds.

Subjects compared the magnitudes of the two target columns of digits. Depending on the format of Display 2, the two target columns could be both from EWM (the *EWM-EWM* condition), both from IWM (the *IWM-IWM* condition), or one from EWM and one from IWM (the *EWM-IWM* condition), as explained in the previous section (see Figure 2). Subjects were instructed to make comparisons from the top to the bottom pair (row) as soon as Display 2 appeared, by pressing the left key if the left digit was larger and the right key if the right digit was larger. Both speed and accuracy were emphasized. The total reaction times (RTs), subjects' decisions, and errors were recorded. The total RT for each trial was also decomposed into individual RTs: the RT for the first comparison was the latency from the onset of Display 2 until the first response; the RT for the second comparison was from the first to the second response; and the RT for the third comparison (for 3-digit columns only) was from the second to the third response.

Design. This is a mixed design. The between-subject factor is column length: 2 digits per column and 3 digits per column. The within-subject factor is representation: *EWM-EWM*, *IWM-IWM*, and *EWM-IWM*. Both length 2 and length 3 conditions have forty-eight trials: sixteen for *EWM-EWM*, sixteen for *IWM-IWM*, and sixteen for *EWM-IWM* (eight for the layout with an external left column and an internal right column, and eight for the opposite layout). The forty-eight trials were completely randomized. Twelve subjects received forty-eight length 2 trials, and twelve other subjects received forty-eight length 3 trials. Every pair of digits to be compared had the same numerical distance of five (e.g., 2 vs. 7) to reduce the variance caused by the distance effect of number comparisons[2]. The pairs of digits to be compared were randomized, with the constraint that the pairs in any given trial were all different.

Results

Trials with errors were excluded from the analyses of RTs. An error occurred if one or more responses of a trial were incorrect. For each subject, the RTs for the sixteen trials for each representation type, after the removal of outliers that deviated from the mean by two standard deviations, were pooled for statistical analyses.

Accuracy. The error rates for *EWM-EWM*, *EWM-IWM*, and *IWM-IWM* were 0.52%, 5.2%, and 5.7% for length 2, and 3.1%, 8.9%, and 4.2% for length 3. A two-way ANOVA for the three representations and two column lengths showed an insignificant interaction ($F(2, 44) = 1.68$, $p = 0.20$), an insignificant length effect ($F(1, 22) = 1.05$, $p = 0.32$), but a significant representation effect ($F(2, 44) = 6.08$, $p = 0.005$). Simple comparisons showed that there were fewer errors for *EWM-EWM* than for *EWM-IWM* ($F(1, 22) = 11.06$, $p = 0.003$) and *IWM-IWM* ($F(1, 22) = 5.66$, $p = 0.03$), which did not differ from each other significantly ($F(1, 22) = 1.67$, $p = 0.21$). A correlation analysis for total RTs and errors within each condition showed that the only significant correlation was a positive one in the *EWM-EWM* length 3 condition ($r = 0.77$, $p = 0.003$). This indicates that the results of RTs were not due to a speed-accuracy trade-off, which would imply a significant negative correlation between RTs and errors.

Total Reaction Time. The total RT for all individual comparisons in a trial is shown in Figure 3A for each condition. A two-way ANOVA for the three representations and two column lengths showed a significant interaction ($F(2, 44) = 9.56$, $p < 0.001$), a significant length effect

($F(1, 22) = 18.10$, $p < 0.001$), and a significant representation effect ($F(2, 44) = 62.66$, $p < 0.001$). The interactions between the two lengths and each pair of representations were analyzed. The interaction between lengths and representations for *EWM-EWM* and *IWM-IWM* was significant ($F(1, 22) = 11.29$, $p < 0.005$), indicating that the increase of column length from 2 to 3 produced a larger RT increase for *IWM-IWM* than for *EWM-EWM*. Similarly, the interaction between lengths and representations for *EWM-IWM* and *IWM-IWM* was also significant ($F(1, 22) = 13.29$, $p < 0.001$), indicating that the increase of column length from 2 to 3 produced a larger RT increase for *IWM-IWM* than for *EWM-IWM*. However, the interaction between lengths and representations for *EWM-IWM* and *EWM-EWM* was not significant ($F(1, 22) = 0.95$, $p = 0.34$), indicating that the increase of column length from 2 to 3 did not produce different RT increases for *EWM-IWM* and *EWM-EWM*.

Separate analyses were carried out for representations and lengths. For every representation type, the total RT for length 3 was significantly larger than that for length 2 (smallest $F(1, 22) = 8.98$ with largest $p < 0.001$). This result was expected because length 3 trials required one more response than length 2 trials. For length 2, the total RT for *EWM-EWM* was significantly smaller than that for *IWM-IWM* ($F(1, 11) = 13.56$, $p < 0.005$) and that for *EWM-IWM* ($F(1, 11) = 39.36$, $p < 0.001$), which did not differ from each other significantly ($F(1, 11) = 0.00$, $p = 0.98$). For length 3, the total RT for *EWM-EWM* was significantly smaller than that for *IWM-IWM* ($F(1, 11) = 86.90$, $p < 0.001$) and that for *EWM-IWM* ($F(1, 11) = 47.32$, $p < 0.001$), and the total RT for *EWM-IWM* was significantly smaller than that for *IWM-IWM* ($F(1, 11) =22.33$, $p < 0.001$).

In sum, the results of total RTs indicate two findings. First, the difficulty orders were, from hardest to easiest, *IWM-IWM* ≈ *EWM-IWM* > *EWM-EWM* for length 2, and *IWM-IWM* > *EWM-IWM* > *EWM-EWM* for length 3. Second, with the increase of column length from 2 to 3, the RT increase for *IWM-IWM* was larger than that for *EWM-IWM* and that for *EWM-EWM*, which did not differ from each other.

Individual Reaction Time. The total RT for each trial was decomposed into individual RTs for the comparisons at different positions. As shown in Figure 3B and 3C, the RTs at the first position for both length 2 and length 3 were substantially larger than latter positions. This is expected because the RTs for the first comparison included initiation latencies, such as the time for selecting the two target columns (for all three representations). For *EWM-IWM* they also included the time for selecting a column to drop from IWM, and for *EWM-EWM* they also included the time for encoding the digits. Because the initiation latencies were not equivalent for different representations, comparing the RTs at the first positions across different representations would not provide unambiguous information. Thus, for length 2 we only considered the individual RTs at the second position, and for length 3 we only considered the individual RTs at the second and third positions. For length 2, the effect of representations was significant at the second position ($F(2, 22) = 7.52$, $p < 0.005$). Separate comparisons showed that the RT for *EWM-EWM* was smaller than that for *IWM-IWM* ($F(1, 11) = 9.65$, $p < 0.01$) and that for *EWM-IWM* ($F(1, 11) = 7.49$, $p = 0.02$), which did not differ from each other ($F(1, 11) = 0.56$, $p = 0.47$). For length 3, a two-way ANOVA for the three representations and the second and third positions showed that the interaction was not significant ($F(2, 22) = 2.42$, $p = 0.11$), the RT at the second position was larger than that at the third position ($F(1, 11) = 15.26$, $p = 0.002$), and the effect of representations was significant ($F(2, 22) = 39.65$, $p < 0.001$). Simple comparisons of representations showed that the following order of RTs: *IWM-IWM* > *EWM-IWM* > *EWM-EWM* (smallest $F(1, 11) = 18.43$ with largest $p < 0.001$).

Although it is not informative to compare the RTs at the first positions across different representations, it is informative to carry out a two-way ANOVA for the two column lengths and the first and second positions within a representation. This is because the initiation latencies for length 2 and length 3 should be the same for the same representation. Figures 3D, 3E, and 3F show the effects of column lengths on RTs for each representation. For *EWM-EWM*, the interaction between lengths and positions was not significant ($F(1, 22) = 0.05$, $p = 0.82$), nor was the effect of lengths ($F(1, 22) = 0.60$, $p = 0.45$). For *IWM-IWM*, the interaction was not significant ($F(1, 22) = 1.79$, $p = 0.19$), but RTs for length 3 was marginally larger than those for length 2 ($F(1, 22) = 3.75$, $p = 0.06$). For *EWM-IWM*, the interaction was not significant ($F(1, 22) = 1.19$, $p = 0.28$), nor was the effect of lengths ($F(1, 22) = 0.10$, $p = 0.75$).

In sum, the analyses of individual RTs suggest the following results. First, the difficulty order was, from hardest to easiest, *IWM-IWM* ≈ *EWM-IWM* > *EWM-EWM* for length 2, and *IWM-IWM* > *EWM-IWM* > *EWM-EWM* for length 3. This was consistent with the result for total RTs. Second, the individual RTs at the second and third positions were different across different representations. Third, the RTs at the second and third positions were different across length 2 and length 3 conditions for *IWM-IWM* but not for *EWM-EWM* and *EWM-IWM*. Fourth, the RTs decreased slightly from the second to the third position.

Insert Figure 3 about here

Discussion

Based on the experimental results, we can infer the comparison mechanisms in the tasks of this experiment. The fact that the individual RTs at the second and third positions were different across different representations indicates that subjects adopted a step-by-step comparison strategy in which they made a single response after each pair of digits were compared, rather than an end-of-sequence comparison strategy in which they made all the responses at the end of sequence after all pairs of digits had been compared. This is due to the following reason. If subjects had made their responses after all pairs had been compared, the individual RTs at the second and third positions would have been identical for all three representations because the RTs for pure responses should be independent of representations.

Although subjects used the same step-by-step comparison strategy for all representations, the strategies for retrieving the pairs of digits for individual comparisons were different for different representations. For *EWM-EWM*, the retrieval of digits for each individual comparison did not depend on column lengths, that is, the RT for each individual comparison for length 2 did not differ from that for length 3 (see Figure 3D). This suggests that the retrieval of digits was a pair-by-pair shifting process. After each comparison, subjects simply shifted their attention to the next pair of digits directly. They did not search more digits in length 3 condition than in the length 2 condition. If they had done so, the RT for each comparison would have been larger for length 3 than for length 2 condition.

For *IWM-IWM*, the retrieval of digits depended on column lengths, that is, the RT for each individual comparison was larger in length 3 condition than in length 2 condition (see Figure 3E). This length effect could be due to the higher cost of memory scanning for length 3 condition than for length 2 condition. That is, in retrieving the two digits for each comparison subjects searched more digits in length 3 condition than in length 2 condition, resulting in larger RTs of individual comparisons for the former than for latter condition. Another possibility is that the length effect was due to the reduced capacity of the central executive in length 3 condition than in length 2 condition. That is, subjects searched the same number of digits in length 3 and length 2 conditions, but the unit time for searching one digit was larger in length 3 condition than in length 2 condition because the higher memory load in length 3 condition reduced the capacity of the central executive to a larger degree than in length 2 condition. We argue that the capacity of the central executive was unlikely to be reduced in this case because the load in length 3 condition was six digits, which were within the limit of working memory capacity. In fact, the third experiment presented later showed that a memory load of six digits did not significantly affect the comparison processes. Thus, the factor responsible for the length effect was memory scanning. The slightly larger RT for the second comparison than the third comparison for length 3 condition suggests that the scanning was not self-terminating. This is because if it were self-terminating, the RT for the third comparison would have been larger than that for the second comparison because it would require scanning more digits for the third comparison than for the second comparison (six vs. five, respectively). We argue that the scanning was exhaustive. An exhaustive scanning should result in identical RTs for the second and third comparisons, which both require scanning six digits. However, because scanning for the second as well as the first comparison was through all six digits in both columns, it could result in preprocessing for the third comparison. Thus, the RT for the third comparison was slightly smaller than that for the second comparison. Exhaustive scanning was also consistent with the maintenance rehearsal of the articulatory loop, which was exhaustive and repetitive.

For *EWM-IWM*, the retrieval of digits for each individual comparison did not depend on column lengths, that is, the RT for each individual comparison did not differ between length 2 and length 3 conditions (see Figure 3F). Similar to *EWM-EWM*, this suggests that the retrieval of digits was a pair-by-pair shifting process. After each comparison, subjects simply shifted their attention to the next pair of digits directly. They did not search more digits in length 3 condition than in length 2 condition. This implies that the scanning of the digits in IWM was a digit-by-digit shifting process. Subjects retrieved a digit from IWM and compared it with the corresponding digit in EWM, then shifted to the next digit in IWM and compared it with next digit in EWM, until they finished all comparisons. This digit-by-digit shifting in IWM was possible because the corresponding digit in EWM could be directly accessed. In contrast, digit-by-digit shifting was impossible in *IWM-IWM* because when the digit in one column was retrieved, the corresponding digit in the other column could not be directly accessed: it had to be retrieved by sequential scanning through the digits in the articulatory loop.

In summary, this experiment shows the following difficulty order: *IWM-IWM* ≥ *EWM-IWM* > *EWM-EWM*. This difficulty order means that given the same amount of information, when more information was in EWM and less information was in IWM, the task became easier. However, the decrease of task difficulty with more information in EWM was not because the capacity of the central executive was increased. Rather, it was because the time for retrieving the digits for each comparison was decreased. This decrease of retrieval time was due to two factors. First, the unit time for scanning a single digit in EWM was smaller than that for scanning a single digit in IWM. This resulted in the difficulty order *EWM-IWM* > *EWM-EWM*. Second, the digits for each comparison in *IWM-IWM* could not be retrieved directly in a digit-by-digit shifting manner. They had to be retrieved by an exhaustive scanning through all the digits in IWM. This exhaustive scanning, combined with the slower latency for scanning a single digit in IWM than in EWM, contributed to the difficulty order *IWM-IWM* ≥ *EWM-IWM*.

Experiment 2

Experiment 2 examines how the encoding of digits in IWM affects the relation between EWM and IWM and whether it changes the difficulty order for the three representations. Experiment 2 was identical to Experiment 1 except that the encoding of digits in IWM was different. Instead of memorizing the digits column by column from the top to the bottom, subjects in Experiment 2 were instructed to memorize the digits on Display 1 (see Figure 2) *column by column in a reversed order*, that is, from the bottom to the top digit on the left column, then from the bottom to the top digit on the right column. Because *EWM-EWM* does not depend on how the digits are encoded in IWM, its results should be identical to those of the same condition in Experiment 1. The results of *IWM-IWM* of the current experiment should be similar to those of the same condition of Experiment 1 because the reversed order should not change the column-by-column encoding that prevents the direct retrieval of the two digits for each comparison. *EWM-IWM* of the current experiment, however, should be different from the same condition in Experiment 1. In Experiment 1, the retrieval of digits from IWM was a digit-by-digit shifting process. In Experiment 2, in contrast, the retrieval of digits from IWM might be an exhaustive process because the bottom-to-top reversed order of encoding in IWM might not allow direct top-to-bottom digit-by-digit shifting.

Method

The subjects were 22 undergraduate students in introductory psychology courses at The Ohio State University who participated in the experiment for course credit. The stimulus, design, and procedure were the same as in Experiment 1, except of the instructions for memorizing the digits on Display 1. In this experiment, subjects were instructed to memorize the digits on

Display 1 column by column in a reversed order, that is, memorize the left column first from the bottom digit to the top digit, then memorize the right column from the bottom digit to the top digit. To ensure that subjects memorized the digits in the instructed order, the digits were presented one at a time, 500 ms per digit, starting from the bottom digit to the top digit of the left column, then the bottom digit to the top digit of the right column. The required response pattern was still from the top row to the bottom row.

Results

Accuracy. The error rates for *EWM-EWM*, *EWM-IWM*, and *IWM-IWM* were 1.7%, 6.3%, and 5.1% for length 2, and 1.1%, 15.9%, and 20.5% for length 3. An ANOVA for representations and lengths showed a significant interaction ($F(2, 40) = 6.31$, $p < 0.005$) and significant effects of lengths ($F(1, 20) = 13.25$, $p < 0.005$) and representations ($F(2, 40) = 14.57$, $p < 0.001$). For length 2, there were fewer errors for *EWM-EWM* than for *IWM-IWM* ($F(1, 10) = 12.00$, $p < 0.01$) and for *EWM-IWM* ($F(1, 10) = 13.91$, $p < 0.005$), which did not differ from each other significantly ($F(1, 10) = 0.65$, $p = 0.44$). Similarly, for length 3, there were fewer errors for *EWM-EWM* than *IWM-IWM* ($F(1, 10) = 20.64$, $p < 0.001$) and *EWM-IWM* ($F(1, 10) = 11.70$, $p < 0.01$), which did not differ from each other significantly ($F(1, 10) = 1.00$, $p = 0.34$). There were more errors for length 3 than length 2 for *IWM-IWM* ($F(1, 20) = 14.46$, $p = 0.001$) and for *EWM-IWM* ($F(1, 20) = 5.18$, $p < 0.05$), but there was no difference in errors between length 3 and length 2 for *EWM-EWM* ($F(1, 20) = 0.24$, $p = 0.63$). A correlation analysis for total RTs and errors within each condition showed that all correlations were positive and none of the them were significant (strongest $r = 0.46$, $p = 0.15$). This indicates that the results of RTs were not due to a speed-accuracy trade-off, which would imply a significant negative correction between RTs and errors.

Total Reaction Time. The total RTs are shown in Figure 4A. An ANOVA for lengths and representations showed a significant interaction ($F(2, 40) = 12.92$, $p < 0.001$) and significant main effects of lengths ($F(1, 20) = 23.20$, $p < 0.001$) and representations ($F(2, 40) = 77.49$, $p <$

0.001). For every pair of representations, the interaction between lengths and representations was significant (smallest $F(1, 20) = 5.60$ with largest $p < 0.05$). This indicates that the increase of column length from 2 to 3 produced a larger RT increase for *IWM-IWM* than for *EWM-IWM* and for *EWM-EWM*, and a larger RT increase for *EWM-IWM* than for *EWM-EWM*. The effect of representations was analyzed for each length and the effect of lengths was analyzed for each representation. For all three representations, as expected, the total RT for length 3 was significantly larger than that for length 2 (smallest $F(1, 20) = 8.33$ with largest $p < 0.01$). For length 2, the total RT for *EWM-EWM* was smaller than that for *IWM-IWM* ($F(1, 10) = 19.48$, $p < 0.001$) and that for *EWM-IWM* ($F(1, 10) = 250.71$, $p < 0.001$), which did not differ from each other ($F(1, 10) = 0.023$, $p = 0.88$). For length 3, the total RT for *EWM-EWM* was significantly smaller that that for *IWM-IWM* ($F(1, 10) = 56.90$, $p < 0.001$) and that for *EWM-IWM* ($F(1, 10) = 126.30$, $p < 0.001$), and the total RT for *EWM-IWM* was significantly smaller than that for *IWM-IWM* ($F(1, 10) = 9.79$, $p < 0.01$).

In sum, the results of total RTs indicate two findings. First, the difficulty orders were, from hardest to easiest, *IWM-IWM* ≈ *EWM-IWM* > *EWM-EWM* for length 2, and *IWM-IWM* > *EWM-IWM* > *EWM-EWM* for length 3. Second, with the increase of column length from 2 to 3, the RT increase for *IWM-IWM* was larger than that for *EWM-IWM*, which in turn was larger than that for *EWM-EWM*.

Individual Reaction Time. The individual RTs are shown in Figures 4B and 4C. Similar to Experiment 1, the individual RTs at the second position were analyzed for length 2 and those at the second and third positions were analyzed for length 3. For length 2, the effect of representations was significant at the second position ($F(2, 20) = 7.78$, $p < 0.005$). Separate analyses showed the RT at the second position for *EWM-EWM* was smaller than that for *IWM-IWM* ($F(1, 10) = 10.10$, $p < 0.01$) and that for *EWM-IWM* ($F(1, 10) = 25.62$, $p < 0.001$), which did not differ from each other significantly ($F(1, 10) = 0.69$, $p = 0.43$). For length 3, a two-way ANOVA for the three representations and the second and third positions showed a significant interaction ($F(2, 20) = 7.07$, $p < 0.005$), a marginally significant effect of positions (F(1, 10) =

4.73, $p = 0.06$), and a significant effect of representations ($F(2, 20) = 36.95$, $p < 0.001$). Separate analyses for each position showed that for both the second and third positions, the differences between all representations were significant (smallest $F(1, 10) = 15.01$ with largest $p < 0.005$). Separate analyses for each representation showed that the RT at the second position was larger than that at the third position for *IWM-IWM* ($F(1, 10) = 11.03$, $p < 0.01$), and the RTs at the second and third positions did not differ from each other for *EWM-IWM* ($F(1, 10) = 1.89$, $p = 0.20$) and for *EWM-EWM* ($F(1, 10) = 0.095$, $p = 0.77$).

Similar to Experiment 1, an ANOVA for the two lengths and the first and second positions was carried out for each representation (see Figures 4D, 4E, and 4F). For *EWM-EWM*, the interaction between length and position was not significant ($F(1, 20) = 0.39$, $p = 0.54$), nor was the effect of lengths ($F(1, 20) = 0.32$, $p = 0.58$). For *IWM-IWM*, the interaction was not significant ($F(1, 20) = 2.81$, $p = 0.11$), but the effect of lengths was significant ($F(1, 20) = 6.78$, $p < 0.05$). For *EWM-IWM*, the interaction was not significant ($F(1, 20) = 0.10$, $p = 0.75$), but the effect of lengths was significant ($F(1, 20) = 7.27$, $p < 0.01$).

In sum, the analyses of individual RTs suggest the following results. First, the difficulty orders were, from hardest to easiest, *IWM-IWM* ≈ *EWM-IWM* > *EWM-EWM* for length 2, and *IWM-IWM* > *EWM-IWM* > *EWM-EWM* for length 3. This was consistent with the result for total RTs. Second, the individual RTs at the second and third positions were different across different representations. Third, the RTs at the second and third positions were different across length 2 and length 3 conditions for *IWM-IWM* and for *EWM-IWM*, but not for *EWM-EWM*. Fourth, the RTs decreased slightly from the second to the third position for *IWM-IWM* but not for *EWM-IWM* and *EWM-EWM*.

Insert Figure 4 about here

Discussion

Most results of this experiment were similar to those of Experiment 1. First, subjects adopted the same step-by-step comparison strategy, as suggested by the result that individual RTs at the second and third positions were different for different representations. Second, in *EWM-EWM* the retrieval of digits was also a pair-by-pair shifting process, as suggested by the result that the RT for each individual comparison did not depend on column lengths (see Figure 4D). In fact, *EWM-EWM* was not affected by how the digits were encoded in IWM because it had nothing to do with the digits in IWM. Third, in *IWM-IWM* the retrieval of digits also depended on column lengths, that is, the RT for each individual comparison was larger in length 3 condition than in length 2 condition (see Figure 4E). Similar to Experiment 1, we again argue that this length effect was due to the higher cost of memory scanning for length 3 than for length 2 condition. That is, in retrieving the two digits for each comparison subjects searched more digits in length 3 than in length 2 condition, resulting in larger RTs of individual comparisons for the former than for latter condition. The larger RT for the second than for the third comparison was consistent with an exhaustive scanning process coupled with preprocessing of the third comparison, as the case in Experiment 1. However, unlike in Experiment 1, it was also consistent with a self-terminating scanning process because subjects needed to scan fewer digits for the third comparison than for the second comparison (four vs. five, respectively) if the scanning was self-terminating. We argue that exhaustive scanning was more likely than self-terminating scanning because an exhaustive, loop-like, and repetitive rehearsal was necessary to maintain the digits in the articulatory loop of IWM.

The result for *EWM-IWM* of the current experiment was different from that for the same condition of Experiment 1. The retrieval of digits for each individual comparison in the current experiment depended on column lengths, that is, the RT for each individual comparison was larger in length 3 condition than in length 2 condition (see Figure 4F). This length effect was due to the cost of memory scanning for the column of digits stored in IWM. In Experiment 1, subjects could use a digit-by-digit shifting process to retrieve the digit in IWM for each comparison because the response order was consistent with the memory scanning order, both from the top to the bottom. In the current experiment, however, the response order was from the top to the bottom but the memory scanning order was from the bottom to the top. Thus, to make the first comparison, subjects needed to scan through all the digits in IWM to retrieve the top digit. Therefore, more digits in a column of IWM caused a larger RT for length 3 condition than for length 2 condition. This memory scanning process appeared to be exhaustive because the RTs for the second and third comparisons did not differ. If the scanning had been self-terminating, the RT for the second comparison would have been larger than that for the third comparison because two digits needed to be scanned for the second comparison but only one digit needed to be scanned for the third comparison.

In summary, this experiment shows the same difficulty order as in Experiment 1: *IWM-IWM* ≥ *EWM-IWM* > *EWM-EWM*. This difficulty order again indicates that given the same amount of information, when more information was distributed in EWM and less information was distributed IWM, the task became easier. As in Experiment 1, the decrease of task difficulty with more information in EWM was not because the capacity of the central executive was increased with the reduction of memory load in IWM. Rather, it was because the time for retrieving the digits for each comparison was reduced. In the current experiment, the difficulty order *IWM-IWM* ≥ *EWM-IWM* > *EWM-EWM* was not only due to the faster unit time for scanning a single digit in EWM than that for scanning a single digit in IWM, but also due to the faster digit-by-digit shifting retrieval in EWM than the exhaustive scanning retrieval in IWM.

Experiment 3

Experiments 1 and 2 both showed that the more information in EWM, the easier the task, that is, *IWM-IWM* > *EWM-IWM* > *EWM-EWM*. The purpose of Experiment 3 is to show that this difficulty order will not always hold. Experiment 3 was identical to Experiment 1 except that the encoding of digits in IWM was different. Instead of memorizing the digits column by column, subjects in Experiment 3 were instructed to memorize the digits on Display 1 (see Figure 2) *row* *by row* from the top to the bottom, that is, memorize the top digit in the left column and the top digit in the right column, until the bottom digit in the left column and the bottom digit in the right column. With this row-by-row encoding in IWM, we expect to get the following results. Because *EWM-EWM* does not depend on how the digits are encoded in IWM, its results should be still identical to those of the same condition in Experiment 1. In *IWM-IWM* of the current experiment however, instead of using an exhaustive scanning strategy, the subjects might use a pair-by-pair shifting strategy for digit retrieval because the encoding order is the same as the response order. In *EWM-IWM* of the current experiment, subjects might still use a pair-by-pair shifting strategy for digit retrieval. However, because only one of the two columns of digits in IWM are target digits for comparison, the non-target digits in the other column of IWM might interfere with the retrieval of the target digits in EWM. Therefore, as a result of the row-by-row encoding of digits in IWM, we might not only get different retrieval strategies, but also get a different difficulty order, which is likely to be *EWM-IWM* > *IWM-IWM* > *EWM-EWM*. This difficulty order would suggest that EWM does not always aid IWM.

Method

The subjects were 24 undergraduate students in introductory psychology courses at The Ohio State University who participated in the experiment for course credit. The stimulus, design, and procedure were the same as in Experiment 1, except of the instructions for memorizing the digits on Display 1. In this experiment, subjects were instructed to memorize the digits on Display 1 row by row, that is, memorize the top digit in the left column and the top digit in the right column, until the bottom digit in the left column and the bottom digit in the right column. The required response pattern was still from the top to the bottom pair (row).

Results

Accuracy. The error rates for *EWM-EWM*, *EWM-IWM*, and *IWM-IWM* were 0.96%, 4.3%, and 2.4% for length 2, and 3.8%, 10.1%, and 5.3% for length 3. An ANOVA for representations and lengths showed an insignificant interaction (F(2, 48) = 0.44, p = 0.65), a significant length effect (F(1, 24) = 10.80, p < 0.005), and a significant representation effect (F(2, 48) = 3.82, p < 0.05). Simple comparisons of representations showed that there were significantly more errors for *EWM-IWM* than for *EWM-EWM* (F(1, 24) = 8.96, p < 0.01), but there were no significant differences in errors between *EWM-IWM* and *IWM-IWM* (F(1, 24) = 2.29, p = 0.14) and between *IWM-IWM* and *EWM-EWM* (F(1, 24) = 1.02, p = 0.32). A correlation analysis for total RTs and errors within each condition showed that the only significant correlation was a positive one in the *IWM-IWM* length 3 condition (r = 0.65, p = 0.02). This indicates that the results of RTs were not due to a speed-accuracy trade-off, which would imply a significant negative correction between RTs and errors.

Total Reaction Time. Similar to Experiment 1, the RTs of each subject were averaged for each representation type before statistical analyses. The total RTs are shown in Figure 5A. An ANOVA for lengths and representations showed a significant interaction (F(2, 48) = 14.23, p < 0.001), a significant length effect (F(1, 24) = 20.19, p < 0.001), and a significant representation effect (F(2, 48) = 75.52, p < 0.001). For every pair of representations, the interaction between lengths and representations was significant (smallest F(1, 20) = 5.96 with largest p < 0.05). This indicates that the increase of column length from 2 to 3 produced a larger RT increase for *EWM-IWM* than for *EWM-EWM* and for *IWM-IWM*, and a larger RT increase for *IWM-IWM* than for *EWM-EWM*. Separated analyses were conducted for representations and lengths. For every representation, the total RT for length 3 was significantly larger than that for length 2 (smallest F(1, 24) = 6.10 with largest p < 0.05). This was an expected result because length 3 trials had one more comparison than length 2 trials. For length 2, the total RT for *EWM-IWM* was larger than that for *EWM-EWM* (F(1, 12) = 60.87, p < 0.001) and that for *IWM-IWM* (F(1, 12) = 43.50, p < 0.001), which did not differ from each other significantly (F(1, 12) = 0.013, p = 0.91). For length 3, the total RT for *EWM-IWM* was significantly larger that that for *IWM-IWM* (F(1, 12) = 54.17, p < 0.001) and that for *EWM-EWM* (F(1, 12) = 68.82, p < 0.001), and the total RT for *IWM-IWM* was significantly larger than that for *EWM-EWM* (F(1, 12) = 11.56, p < 0.005).

In sum, the results of total RTs indicate two findings. First, the difficulty orders were, from hardest to easiest, *EWM-IWM* > *IWM-IWM* ≈ *EWM-EWM* for length 2, and *EWM-IWM* > *IWM-IWM* > *EWM-EWM* for length 3. These difficulty orders were different from those in Experiments 1 and 2, which were *IWM-IWM* ≈ *EWM-IWM* > *EWM-EWM* for length 2 and *IWM-IWM* > *EWM-IWM* > *EWM-EWM* for length 3. Second, with the increase of column length from 2 to 3, the RT increase for *EWM-IWM* was larger than that for *IWM-IWM*, which in turn was larger than that for *EWM-EWM*. This was also different from that in Experiments 1 and 2, in which the RT increase for *IWM-IWM* was larger than that for *EWM-IWM*, which in turn was larger than that for *EWM-EWM*.

Individual Reaction Time. The individual RTs are shown in Figures 5B and 5C. Similar to Experiments 1 and 2, the individual RTs at the second position were analyzed for length 2 and those at the second and third positions were analyzed for length 3. For length 2, the effect of representations was significant at the second position ($F(2, 24) = 29.65$, $p < 0.001$). Separate analyses showed the following order of RTs at the second position: *EWM-IWM* > *IWM-IWM* > *EWM-EWM* (smallest $F(1, 12) = 19.99$ with largest $p < 0.001$. For length 3, a two-way ANOVA for the three representations and the second and third positions showed that the interaction was not significant ($F(2, 24) = 0.56$, $p = 0.58$), the RTs for the second position were larger than those at the third position ($F(1, 12) = 7.65$, $p = 0.02$), and the effect of representations was significant ($F(2, 24) = 52.88$, $p < 0.001$). Separate comparisons for representations showed the following order of RTs for the second and third positions: *EWM-IWM* > *IWM-IWM* > *EWM-EWM* (smallest $F(1, 12) = 27.96$ with largest $p < 0.001$).

A two-way ANOVA for the two column lengths and the first and second positions was carried out for each representation (Figures 5D, 5E, and 5F). For all three representations, none of the interactions between lengths and positions were significant (largest $F(1, 24) = 2.55$ with smallest $p = 0.12$), nor was the effect of lengths (largest $F(1, 24) = 2.72$ with smallest $p = 0.11$).

In sum, the analyses of individual RTs suggest the following results. First, the difficulty order was, from hardest to easiest, *EWM-IWM* > *IWM-IWM* > *EWM-EWM* for both length 2 and length 3. Second, the individual RTs at the second and third positions were different across different representations. Third, the RTs for length 2 and length 3 did not differ at the first and second positions for any of the three representations. Fourth, the RTs decreased slightly from the second to the third position.

Insert Figure 5 about here

Discussion

The results of the current experiment were similar to those of Experiments 1 and 2 only in the following two aspects. First, subjects adopted the same step-by-step comparison strategy for all representations, as suggested by the different individual RTs across different representations. Second, in *EWM-EWM* the retrieval of digits was also a pair-by-pair shifting process, as suggested by the result that the RT for each individual comparison did not depend on column lengths (see Figure 5D). Again, *EWM-EWM* was not affected by how the digits were encoded in IWM.

The processes of retrieving digits in *IWM-IWM* and *EWM-IWM* of the current experiment were different from those in Experiments 1 and 2. In *IWM-IWM* of the current experiment, the retrieval of digits did not depend on column lengths, that is, in retrieving the two digits for each comparison subjects did not search more digits in length 3 than in length 2 condition (see Figure 5E). This insignificant length effect suggests that the retrieval of digits for each comparison was a pair-by-pair shifting process. This was a natural result because the digits in IWM were memorized row-by-row. In *EWM-IWM*, the retrieval of digits for each individual comparison did not depend on column lengths, that is, in retrieving the two digits for each comparison subjects did not search more digits in length 3 than in length 2 condition (see Figure 5F). Although only one of the two columns of digits in IWM was needed for the task, subjects did not reorganize the digits in IWM to remove the non-target column of digits. If subjects had reorganized the digits in IWM to remove the non-target column of digits, the RT for the first comparison would have been very high. In addition, the RTs for the second and third comparisons would have been smaller than those in *IWM-IWM* because with the removal of the non-target column of digits the second and third comparisons would be identical to those in *IWM-IWM* of Experiment 1. The actual result, however, showed that in *EWM-IWM* the RT for the first comparison was not very high and the RTs for the second and third comparisons, rather than smaller, were larger than those in *IWM-IWM*. Therefore, the insignificant length effect suggests that the retrieval of digits for each comparison in *EWM-IWM* was a pair-by-pair shifting process even if only one of the two digits in a pair was needed for the comparison.

In Experiments 1 and 2, *IWM-IWM* was more difficult than *EWM-IWM*. In the current experiment, however, the difficulty order was reversed. The difficulty of *EWM-IWM* in the current experiment was most likely due to interference. Although only one of the two columns of digits in IWM was needed, both columns were maintained due to the row-by-row memorization procedure. Thus, when subjects retrieved the digit in IWM for each comparison, they also scanned the other non-target digit in the row. Because the non-target digit in IWM occupied the same position as the target digit in EWM, it could interfere with the retrieval of the target digit in EWM. As a result of the interference, it took longer to compare a pair of digits in *EWM-IWM* than a pair of digits in *IWM-IWM*.

In summary, this experiment showed a difficulty order that was different from that in Experiments 1 and 2: *EWM-IWM* > *IWM-IWM* > *EWM-EWM*. This difficulty order was inconsistent with the general claim that the more information in external representations, the easier the task. In other words, external working memory does not always enhance task performance. When all digits were in EWM, the task was still the easiest, due to the faster unit time for scanning a single digit in EWM than that for scanning a single digit in IWM, as suggested by the difficulty order *IWM-IWM* > *EWM-EWM*. However, the task in which one column of digits was in EWM and the other was in IWM was more difficult than the task in which both columns of digits were in IWM, due to the interference between the target digits in EWM and the non-target digits in IWM.

General Discussion

The Memory Aid Hypothesis

The three experiments carried out in the present study directly and explicitly tested the memory aid hypothesis of external representations. The results show that external representations could hinder as well as enhance task performance. Specifically, a task with all information in EWM was always easier than a task with part or all information in IWM, but a task with information distributed across IWM and EWM could be easier or harder than a task with all information in IWM, depending on how the information in IWM was encoded. Therefore, the memory aid hypothesis of external representations is not always true and cannot be taken for granted.

Difficulty Factors

The critical factor that determined the difficulty of a task was the retrieval of information from EWM and IWM. The strategies of retrieval were not the same for all cases. They were determined by how the representation was distributed across EWM and IWM and how the information in IWM was encoded. For *EWM-EWM*, the retrieval was always a pair-by-pair shifting process. For *IWM-IWM*, the retrieval was an exhaustive scanning process when the digits in IWM were encoded column by column, but it became a pair-by-pair shifting process when the digits in IWM were encoded row by row. For *EWM-IWM*, the retrieval of digits from EWM was always a digit-by-digit shifting process. However, the retrieval of digits from IWM was a digit-by-digit shifting process when the digits in IWM were encoded column by column from the top to the bottom, an exhaustive scanning process when they were encoded column by column from the bottom to the top, and a pair-by-pair shifting process when they were encoded row by row. These different retrieval strategies required different latencies, which resulted in different difficulty levels for these tasks.

The Relation between IWM and EWM

The different retrieval strategies for different representation types and different encodings in IWM reflect the differences between EWM and IWM. EWM is a separate component that is different from IWM, and the information in EWM needs not to be re-represented in IWM. This is supported by the different retrieval strategies for EWM and IWM. If the information in EWM needs to be re-represented in IWM, then *EWM-EWM* should be more difficult than *IWM-IWM* because re-representation requires extra effort. However, the experiments showed that *EWM-EWM* was always easier than *IWM-IWM* regardless of how the digits in IWM were encoded, suggesting that subjects did not first re-represent the two columns of digits in EWM into IWM and then made the comparisons in IWM. The processing mechanisms for EWM and IWM are also different: for EWM they are perceptual processes whereas for IWM they are memorial processes. The explicit separation of EWM and IWM is consistent with the view of situated cognition (e.g., Barwise & Perry, 1983; Clancey 1993; Greeno, 1989; Greeno & Moore 1993; Lave, 1988; Lewis, 1991; Suchman, 1987), which argues that it is not necessary to construct an internal model of the external environment to perform cognitive tasks: people can directly access the situational information in the external environment and act upon it in an adaptive manner. It is also consistent with the view of distributed representations (Zhang & Norman, 1994, 1995; Zhang, 1996, 1997, in press), which argues that the representation of a cognitive task involving external representations is neither solely internal nor solely external, but distributed as a system of distributed representations with internal and external representations as two indispensable parts.

The different retrieval strategies for different representation types and different encodings in IWM also reflect the interactions between EWM and IWM. Although EWM and IWM are separate components, they can interact with each other. For example, Experiment 3 of the current study showed that the retrieval of information from IWM could interfere with the retrieval of information from EWM. We argued that this interference resulted from the same spatial positions indexed by both EWM and IWM.

The Organization of Behavior

The fact that subjects did not first re-represent all the information in EWM into IWM and then made comparisons in IWM suggests that subjects were minimizing the load of IWM during the comparison tasks. They did not process even slightly more information than necessary at any instant although they had the ability to re-represent all the information in EWM into IWM in the comparison tasks. The digit-by-digit retrieval strategy for EWM indicates that only the information needed at a specific moment was retrieved on-line. This finding is consistent with the eye movement data of the block-copying experiments by Ballard, Hayhoe, Pook, & Rao (in press), in which subjects needed to construct a block pattern which was identical to a given model. They found that subjects used frequent eye movements to make maximum use of the information in the environment and avoided even modest demands on working memory. They argue that such on-demand, on-line, and incremental acquisition of external information through eye movements, which they called deictic computation, is a fundamental process that links the external environment with internal cognitive mechanisms.

Another result of our current experiments is that subjects adopted a step-by-step comparison strategy for all representations, regardless of whether the load in IWM was high (e.g., *IWM-IWM*) or low (e.g., *EWM-EWM*). We argue that this is because the step-by-step comparison strategy minimizes the load of IWM at any instant. In contrast, the end-of-sequence comparison strategy increases the load in IWM because it requires the storage of comparison results in IWM so that responses can be made after all comparisons have been made.

Taken together, the different retrieval strategies for different representations and the same comparison strategy for all representations suggest that the pattern of behavior was a result of constraint satisfaction--a process that minimizes the load of IWM and meanwhile satisfies the constraints set by specific representations. This result is slightly different from the finding of the list-processing experiments by Carlson, Wenger, & Sullivan (1993). In their experiments, subjects did not adopt an end-of-sequence reporting strategy, that is, they avoided increasing the load of IWM. This is consistent with the minimization of IWM load hypothesis. However, they did not adopt a strict step-by-step reporting strategy to keep the load of IWM at a minimum level. The chunking strategy that subjects adopted kept the load of IWM low but not minimum. Nevertheless, this chunking strategy did minimize the switching cost of activities. Thus, subjects appeared to minimize a cost, but this cost is a combined cost of IWM load and activity switching.

Concluding Remarks

We extended Baddeley's original working memory framework to a preliminary framework of DWM to address the relations between external representations and working memory. Although most details of the DWM framework remain to be specified, our study shows that the extension is necessary. The DWM framework provides a new conceptual language to describe the relations between external representations and working memory, which is not available from the original working memory framework. In addition, our experimental results show that EWM is a separate component that is qualitatively different from IWM. It has different processing mechanisms, activates different procedures and strategies, interacts with IWM, and directly participates in the organization of behavior through the minimization of IWM load. For cognitive tasks that involve external representations, the "working space" is not the working memory in the traditional sense. It is the DWM that consists of IWM and EWM as two indispensable components.

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Footnotes

[1] Although EWM can also be auditory, we only consider visual EWM in the present study.

[2] The distance effect is that the time to compare the magnitudes of two 1-digit numbers decreases with the numerical distance between them (Moyer & Landauer, 1967; for reviews, see Banks, 1977; Moyer & Dumais, 1978)

Author Notes

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Figure Captions

Figure 1. The framework of distributed working memory.

Figure 2. The stimuli for the three experiments.

Figure 3. Results of Experiment 1. 1st, 2nd, and 3rd indicate the individual comparisons.

Figure 4. Results of Experiment 2. 1st, 2nd, and 3rd indicate the individual comparisons.

Figure 5. Results of Experiment 3. 1st, 2nd, and 3rd indicate the individual comparisons.

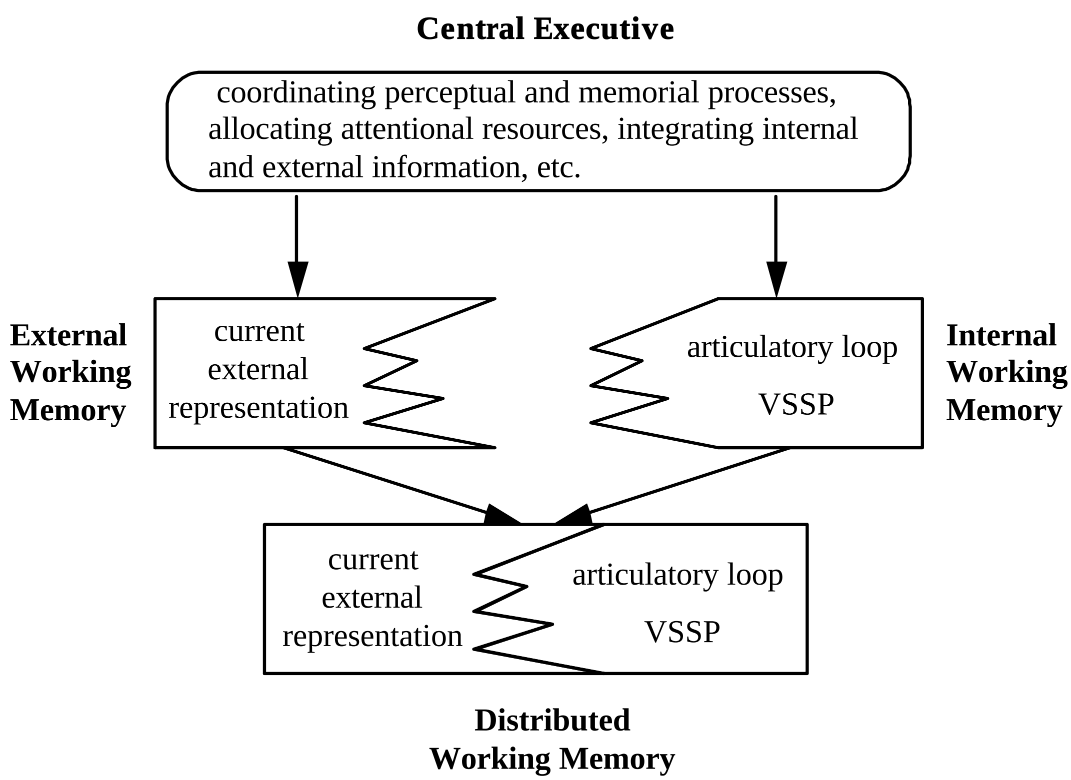

Central Executive
coordinating perceptual and memorial processes, allocating attentional resources, integrating internal and external information, etc.
External Working Memory
current external representation
articulatory loop
VSSP
Internal Working Memory
current external representation
articulatory loop
VSSP
Distributed Working Memory

Figure 1

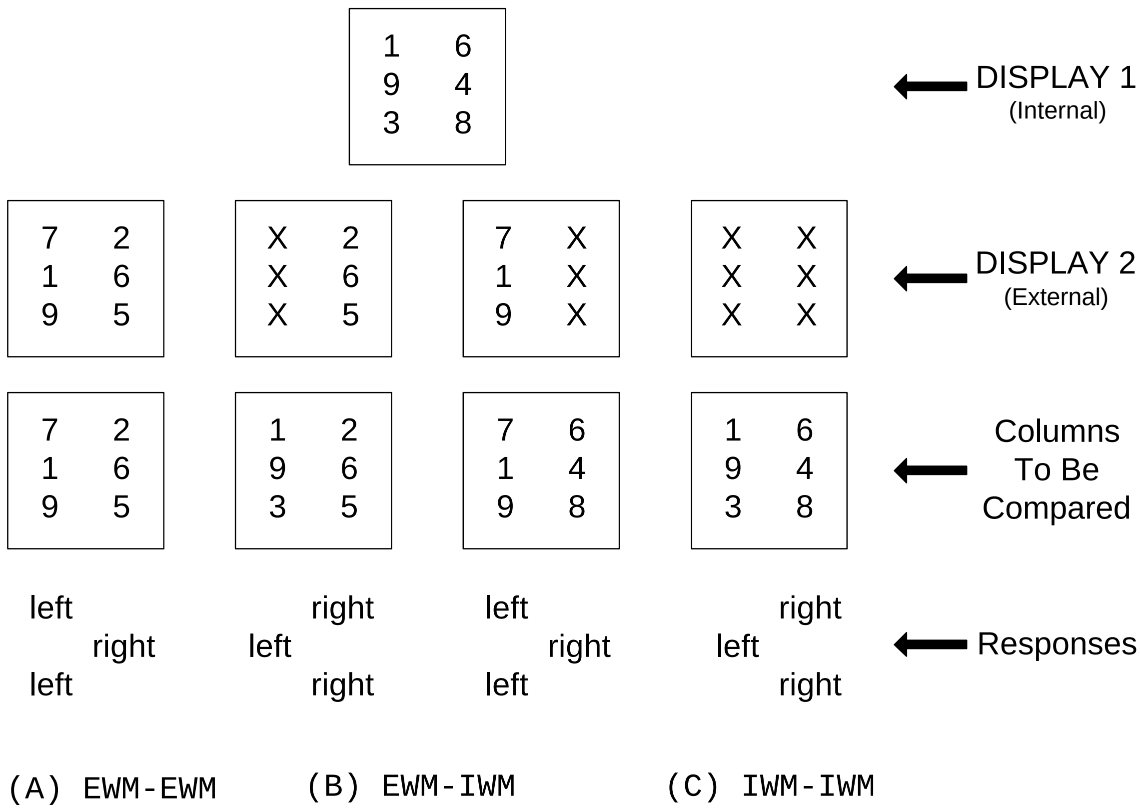

1 6
9 4
3 8
DISPLAY 1
(Internal)
7 2
1 6
9 5
X 2
X 6
X 5
7 X
1 X
9 X
X X
X X
X X
DISPLAY 2
(External)
7 2
1 6
9 5
1 2
9 6
3 5
7 6
1 4
9 8
1 6
9 4
3 8
Columns
To Be
Compared
left
right
left
right
left
right
left
right
left
right
left
right
Responses
(A) EWM-EWM
(B) EWM-IWM
(C) IWM-IWM

Figure 2

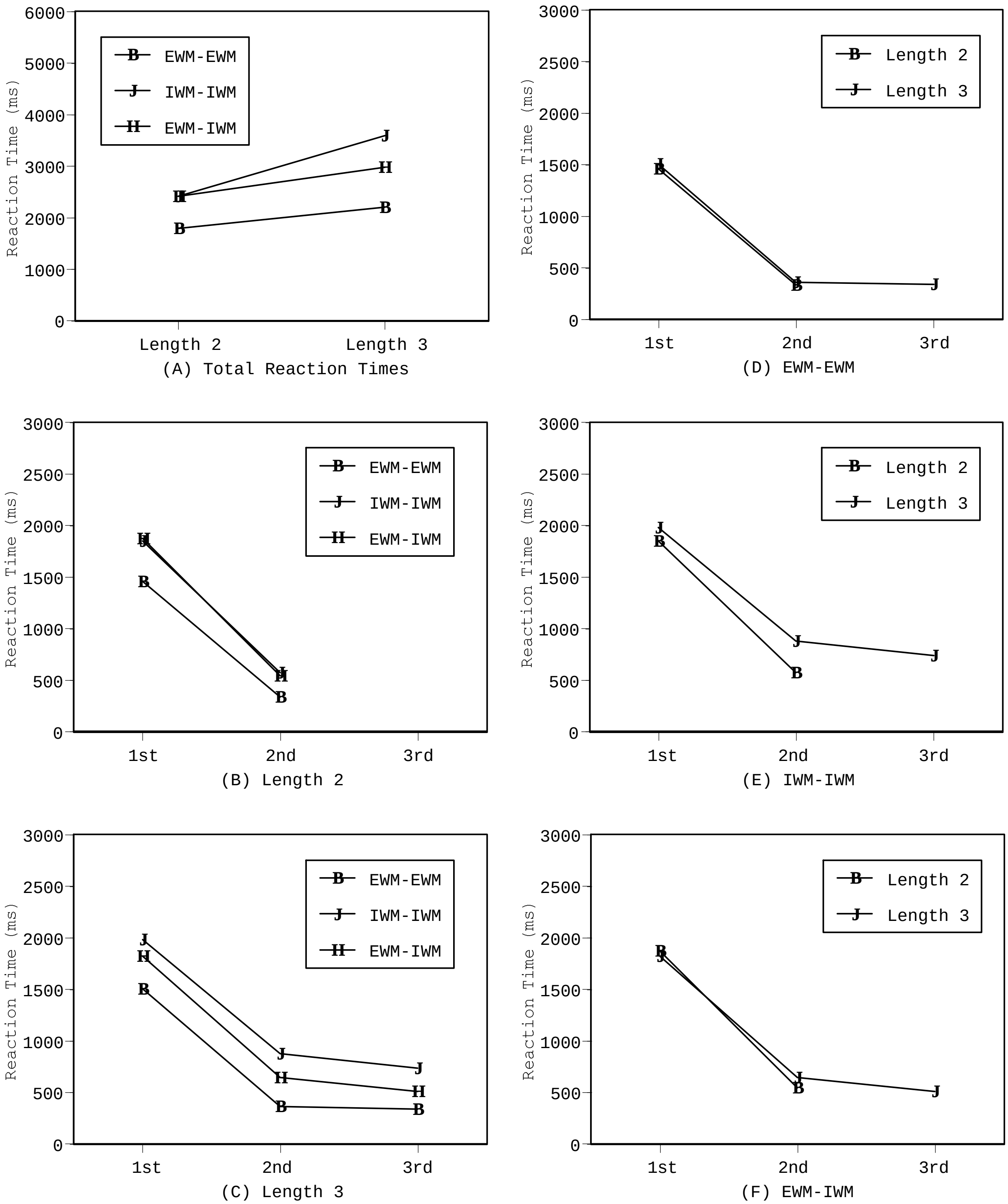
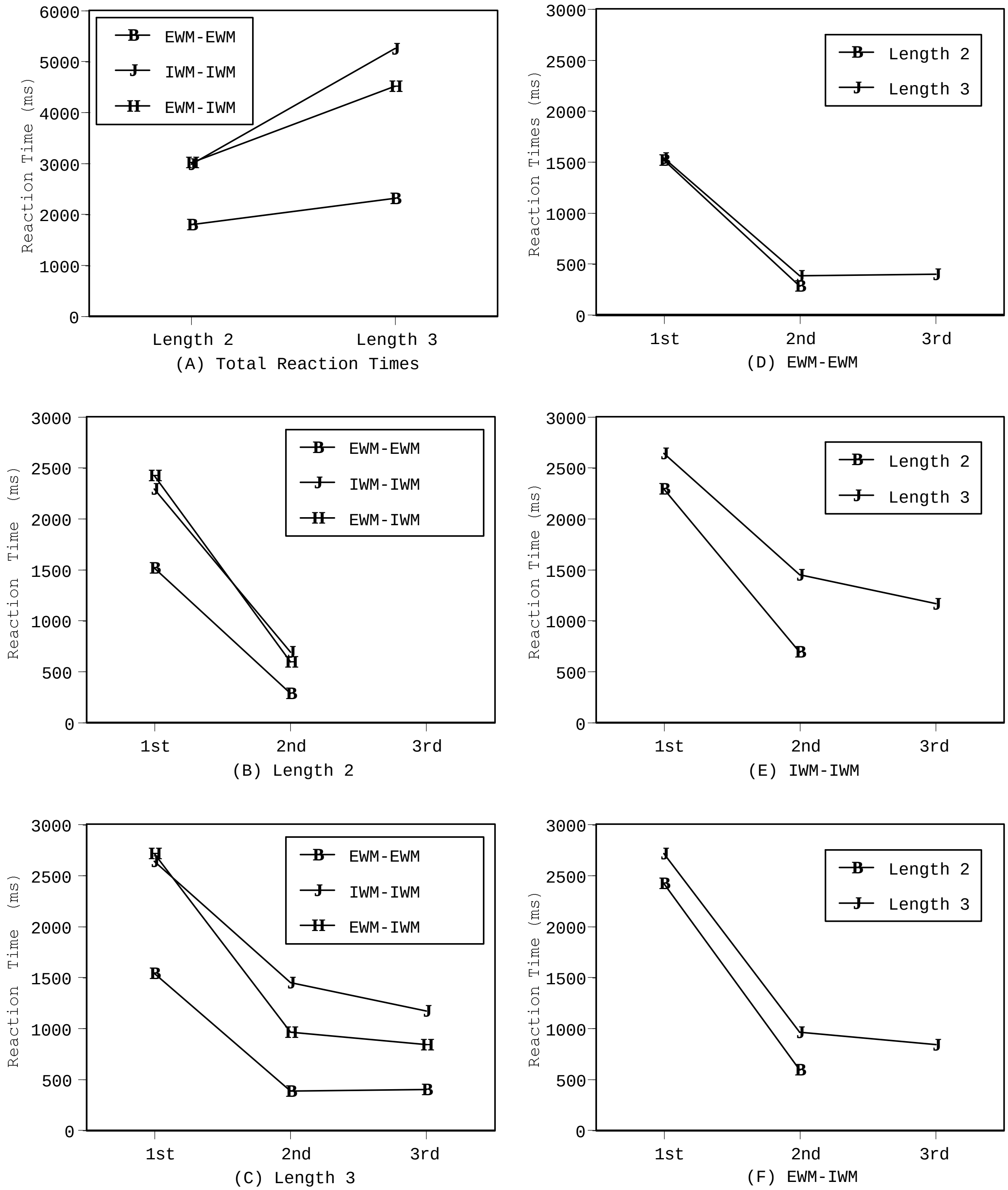

Reaction Time (ms)
0
1000
2000
3000
4000
5000
6000
B EWM-EWM
J IWM-IWM
H EWM-IWM
Length 2
Length 3
(A) Total Reaction Times
Reaction Time (ms)
0
500
1000
1500
2000
2500
3000
B Length 2
J Length 3
1st
2nd
3rd
(D) EWM-EWM
Reaction Time (ms)
B EWM-EWM
J IWM-IWM
H EWM-IWM
1st
2nd
3rd
(B) Length 2
Reaction Time (ms)
B Length 2
J Length 3
1st
2nd
3rd
(E) IWM-IWM
Reaction Time (ms)
B EWM-EWM
J IWM-IWM
H EWM-IWM
1st
2nd
3rd
(C) Length 3
Reaction Time (ms)
B Length 2
J Length 3
1st
2nd
3rd
(F) EWM-IWM

Figure 3



Reaction Time (ms)
EWM-EWM
IWM-IWM
EWM-IWM
Length 2
Length 3
(A) Total Reaction Times
Reaction Times (ms)
Length 2
Length 3
1st
2nd
3rd
(D) EWM-EWM
Reaction Time (ms)
EWM-EWM
IWM-IWM
EWM-IWM
1st
2nd
3rd
(B) Length 2
Reaction Time (ms)
Length 2
Length 3
1st
2nd
3rd
(E) IWM-IWM
Reaction Time (ms)
EWM-EWM
IWM-IWM
EWM-IWM
1st
2nd
3rd
(C) Length 3
Reaction Time (ms)
Length 2
Length 3
1st
2nd
3rd
(F) EWM-IWM

Figure 4

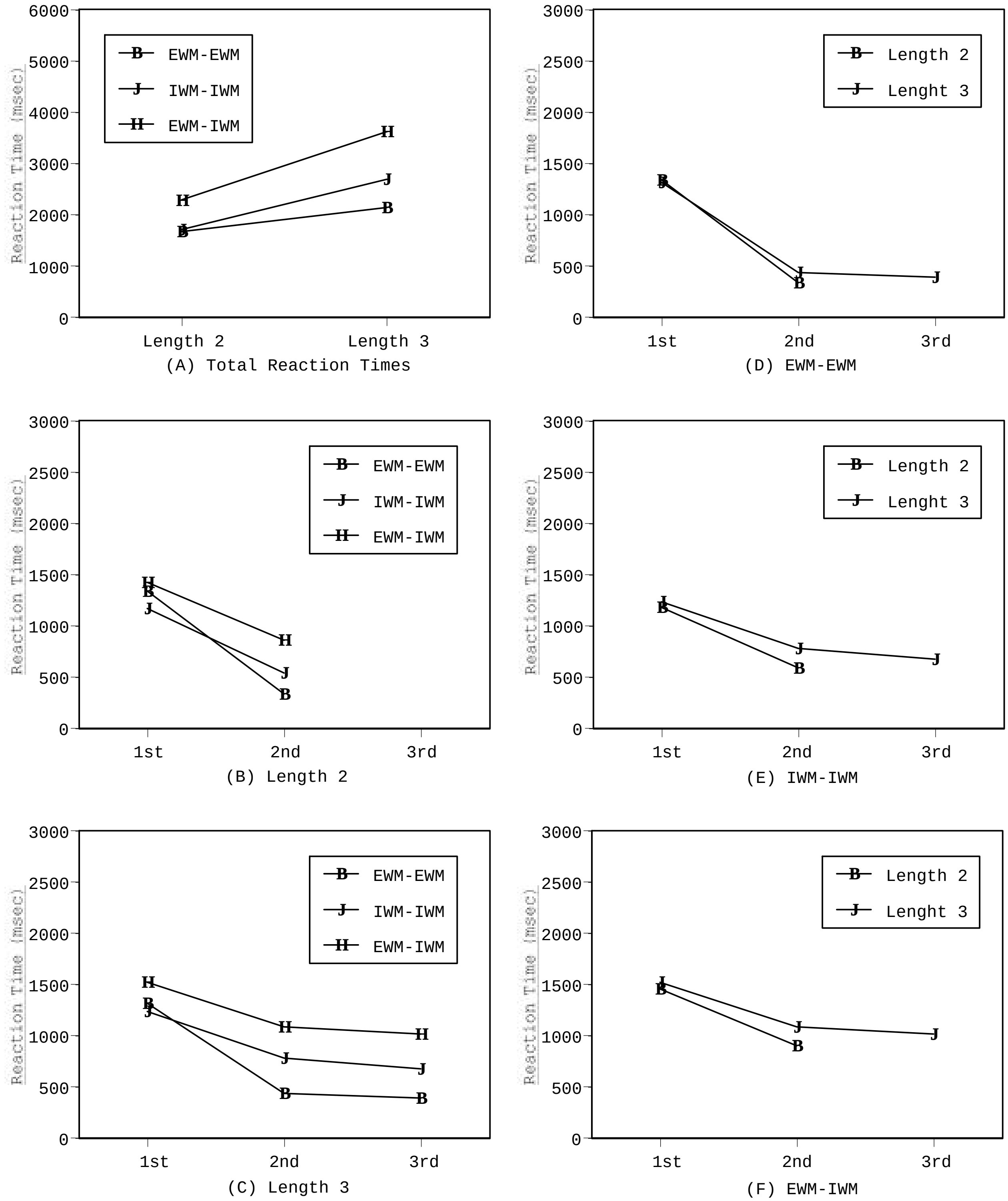

Reaction Time (msec)
EWM-EWM
IWM-IWM
EWM-IWM
Length 2
Length 3
(A) Total Reaction Times
Length 2
Lenght 3
1st
2nd
3rd
(D) EWM-EWM
(B) Length 2
(E) IWM-IWM
(C) Length 3
(F) EWM-IWM

Figure 5