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Complexity Effects in Visuo-spatial Working Memory: Implications for the Role of Long-term Memory

Eva Kemps
University of Ghent, Belgium

Running Head: LTM Processes in Visuo-spatial WM

Mailing address: Eva Kemps
Department of Experimental Psychology
University of Ghent
Henri Dunantlaan 2, B-9000 Ghent
Belgium
Phone: +32-(0)9- 264 64 06
Fax: +32-(0)9- 264 64 96
E-mail: Eva.Kemps@rug.ac.be

ABSTRACT

Several studies have shown that the capacity of visuo-spatial working memory is limited by complexity. Using a variant of the Corsi blocks task, this paper investigated the effect of complexity of the to-be-remembered path on visuo-spatial memory span. Redundancy was determined by three Gestalt principles: symmetry, repetition and continuation. Experiment 1 revealed an effect of path complexity. The subsequent experiments explored whether the superiority for recall of structured over complex paths can be attributed solely to the operation of visuo-spatial working memory, or whether it also reflects the use of long-term knowledge. Experiment 2 demonstrated that the effect of complexity remained, even when the mechanisms for visuo-spatial coding were removed by a secondary visuo-spatial task. In Experiments 3 and 4 subjects were trained in the recall of complex paths. This led to the creation of long-term memory representations for these paths, as shown by an improvement in their span, and a concomitant lack of transfer to new paths. Finally, Experiment 5 showed that one prior repetition of a complex path was sufficient to produce specific and long-term learning effects. These results point to the involvement of long-term memory processes in the temporary retention of visuo-spatial material for which representations exist in long-term memory. They also suggest that the effect of complexity may provide a tractable technique for investigating the mechanisms underlying the limits of visuo-spatial short-term storage.

INTRODUCTION

Baddeley and Hitch (1974; Baddeley, 1986) introduced a multi-component architecture of working memory to provide an adequate explanation for a variety of short-term memory phenomena which the contemporary assumption of a unitary short-term memory system (Atkinson & Shiffrin, 1968) failed to accommodate. The working memory model comprises three components: a central executive and two slave systems, the phonological loop and the visuo-spatial sketch pad. This view of short-term memory has produced a vast amount of research, the lion's share of which has been devoted to the phonological loop.

The central executive is a limited-capacity attentional system. It controls and co-ordinates the functions of the slaves. Although the central executive certainly awaits further exploration, a number of attention demanding techniques have been developed to address the functioning of this system, such as the random generation tasks (e.g., Baddeley, 1966; Baddeley, Emslie, Kolodny, & Duncan, 1998; Gilhooly, Logie, Wetherick, & Wynn, 1993; Vandierendonck, De Vooght, & Van der Goten, 1998).

The phonological loop is responsible for the temporary storage of verbal material in a phonological code, supported by an articulatory rehearsal mechanism. The concept of the phonological loop is based on evidence from laboratory phenomena, such as the phonological similarity effect (Conrad, 1964), the unattended speech effect (Salamé & Baddeley, 1982), the word length effect (Baddeley, Thomson, & Buchanan, 1975), and the effect of articulatory suppression (Levy, 1971). The development of the model has also benefited from research in children (e.g., Hulme, Thomson, Muir, & Lawrence, 1984; Nicolson, 1981) and patients with selective verbal short-term memory deficits (e.g., Shallice & Warrington, 1970; Vallar & Baddeley, 1984).

The visuo-spatial sketch pad is involved in the temporary retention of visuo-spatial information. Theoretical development of this slave system has progressed less rapidly. However, during the last decade considerable insight has been gained into the characteristics of the visuo-spatial component. For example, it has been shown to involve resources distinct from both the phonological loop (Logie, Zucco, & Baddeley, 1990) and the central executive (Farmer, Berman, & Fletcher, 1986). Several studies have demonstrated the involvement of visuo-spatial working memory in movement planning and control (e.g., Quinn, 1994; Quinn & Ralston, 1986; Smyth, Pearson, & Pendleton, 1988; Smyth & Pendleton, 1989). After an initial debate on the spatial (Baddeley & Lieberman, 1980) versus the visual (Logie, 1986)

nature of the sketch pad, subsequent research efforts have shown that visuo-spatial working memory is sensitive to both visual and spatial tasks (Baddeley, 1988). Results from double dissociation experiments are consistent with separate yet interdependent visual and spatial temporary memory systems (e.g., Logie & Marchetti, 1991; Tresch, Sinnamon, & Seamon, 1993). Logie (1995) recently suggested that visuo-spatial working memory comprises two functional components: a passive visual store (visual cache) and an active spatial rehearsal mechanism (inner scribe). The cache is subject to decay and visual interference. The scribe is associated with movement processes and helps maintain the contents of the store. This view of visuo-spatial working memory mirrors the conceptual distinction between a phonological store and an articulatory rehearsal process in verbal working memory.

The limitations on verbal short-term memory are expressed in terms of temporal duration. The capacity of the phonological store is limited to the amount of spoken material that can be rehearsed in a time interval of about two seconds (Baddeley et al., 1975; Schweikert & Boruff, 1986; Standing, Bond, Smith, & Isely, 1980). The storage capacity of visuo-spatial working memory, however, is not measured in units of time (Smyth & Scholey, 1992, 1994).

A variety of sources point to the concept of complexity as a measure of visuo-spatial working memory capacity. For example, Wilson, Scott, and Power (1987) reported an effect of complexity on recognition memory span for matrix patterns. On each trial subjects were shown a matrix pattern with half of the squares of the matrix filled at random. It was then removed and subsequently shown again, but with one of the previously filled squares left blank. Subjects were instructed to indicate which square had been changed. The complexity of the patterns was systematically raised over trials by increasing the total number of squares in the matrix up to a point where performance failed. Subjects could successfully identify the position of the changed square from a matrix with fourteen filled squares. In a subsequent study, Logie et al., (1990) showed that performance on the matrix span task was selectively impaired by a concurrent visuo-spatial task. The authors interpreted their results as being consistent with the notion of a visuo-spatial storage mechanism, whose capacity is limited by pattern complexity.

In the previous studies complexity was defined in terms of the number of pattern elements in a matrix, and thus constitutes a quantitative measure of the concept. However, complexity could also pertain to the degree of internal coherence contained within a stimulus. For example, research efforts within the framework of information-theory (Attneave, 1955;

Schnore & Partington, 1967) found recall of dot-in-matrix patterns to be a linear function of the degree of symmetry manifest in the patterns. Research on complexity judgements of matrix patterns has in fact shown that the concept of complexity is determined by both a quantitative and a structural factor (Chipman, 1977; Ichikawa, 1985). The former sets an upper bound on complexity, whereas the latter reduces complexity. Quantitative complexity includes aspects such as the number of elements in a stimulus, the size of a stimulus, etc. Structural complexity is related to the redundancy of a stimulus. A stimulus is redundant if parts of it can be predicted from other parts. Gestalt factors including symmetry, good continuation and other forms of regularity constitute redundancy.

Recent work by Kemps (1999) reported effects of both quantitative and structural measures of complexity on visuo-spatial memory span. Variants of the Corsi blocks task were used across a series of experiments. This task has proven to be a useful technique for assessing nonverbal memory (e.g., De Renzi & Nichelli, 1975; Milner, 1971; Orsini et al., 1986; Smyth & Scholey, 1992, 1994), and has been shown to tap the resources of visuo-spatial working memory (Hanley, Young, & Pearson, 1991). Quantitative complexity was induced through the number of blocks on the board. Structural complexity was manipulated through the positioning of the blocks. Visuo-spatial span was found to be inversely related to the number of blocks on the board. Recall scores were also higher when the blocks were positioned in a matrix than in a random fashion.

The present study sought to gain further insight into the limitations on visuo-spatial short-term retention in terms of complexity. In addition to the two kinds of complexity induced by the display, the Corsi blocks task elicits yet a third measure of complexity: the complexity of the to-be-remembered block sequence, or path. Disregarding the quantitative element, number of presented blocks, the path constitutes a structural measure of complexity. The complexity of the path is determined by the positions and spatial relationships among its constituent blocks. Depending on the degree of redundancy evoked by the sequence of movements, the path will be more or less complex.

A related issue was put forward by Smirni, Villardita, and Zappala (1983). They showed that performance on the Corsi blocks task not only depends on the length of the to-be-remembered path, but also on its spatial configuration, generated by the chosen digit sequences. Smirni et al. (1983) recommend using paths of homogeneous difficulty to reduce the effect of path characteristics, and thus ensure a more objective measure of visuo-spatial memory span.

The aim of the following experiments was to explore the effect of path complexity on immediate visuo-spatial recall, and to investigate its use as a technique to unravel the mechanisms underlying short-term visuo-spatial retention. An adapted version of the Corsi blocks task was used to present the sequences. The complexity of the display, in terms of the number of blocks on the board and their positioning, was kept constant.

EXPERIMENT 1

Experiment 1 addressed the effect of path complexity in a modified span procedure. The complexity of the path was operationally defined in terms of redundancy. Two types of paths comprising respectively simple and complex spatial configurations were constructed. The simple paths yielded interdependencies among their parts, and henceforth will be referred to as structured. By contrast, the spatial configuration of the complex paths revealed no perceptual organisation whatsoever. It was hypothesised that memory span would be higher for structured than for complex paths. A structured path contains less information than a complex one, because, part of the path can be predicted from other parts, and should therefore be easier to reproduce from memory than a complex path.

Method

Subjects and Design

Twenty-six first-year students at the Faculty of Psychology and Educational Sciences of the University of Ghent participated for course requirements and credit. Subjects were tested individually in a repeated measures design. The independent factor was the complexity of the path (structured, complex).

Materials

Twenty-five black blocks (4 x 4 x 4 cm) were positioned on a black wooden board (40 x 40 cm) in a regular 5 x 5 matrix. The blocks were numbered from 1 to 25; these numbers could be seen by the experimenter, but not by the subject. Path complexity was determined by three Gestalt principles: 1. *Symmetry* – the spatial pattern generated by the targeted movements is symmetrical about the horizontal, the vertical, and/or the 45º axes of the matrix

display; 2. *Repetition* - one part of the block sequence is repeated in translated positions, whether or not transformed (i.e., reflected or rotated); and 3. *Continuation* - the targeted block positions create a continuous form in that there are no path crossings. The structured paths comprised at least one of these forms of redundancy. The complex paths were in no way redundant. Examples of structured and complex block sequences are shown in Figure 1.

Insert Figure 1 about here

Procedure

Subjects were tested individually in a quiet room. They were given instructions about the task and were given a few practice trials. The experimenter touched a series of blocks at a rate of one block per second. Subsequently the subject was required to touch the same blocks in their order of presentation. Subjects were given six trials at each span length from 3 to 8 items, comprising three structured trials and three complex trials, the order of which was randomised. No block was presented more than once on any one trial. Memory span was calculated based on a measure employed by Smyth and Scholey (1992). Each correct trial counted as $^1/_3$; the total number of thirds was added to 2 (the sequence length below starting level) to yield a span score. Two sets of visuo-spatial sequences were constructed; half the subjects were given set A, the other half set B.

Results

In accordance with McCall and Appelbaum's (1973) suggestions for a correct statistical analysis of repeated measures designs, a multivariate analysis was performed with the recall measures obtained in the two complexity conditions as the dependent variables. There was a main effect of complexity, $F(1,25) = 85.21$, $P < .001$. Span scores were higher for the structured ($M = 5.95$, $SD = 0.74$) than for the complex trials ($M = 4.73$, $SD = 0.59$). Moreover, the longer the sequence the larger the discrepancy in performance between the structured and the complex paths. Mean number of correct trials at each sequence length is shown in Figure 2.

Insert Figure 2 about here

Discussion

The complexity of the to-be-remembered path imposed a limit on the serial recall of block sequences. This finding suggests that the representation of a redundant path is more compact, and thus takes up less storage capacity of the visuo-spatial slave system than that of a complex path. Therefore, when the path constitutes some form of redundancy, more items can be held in the short-term visuo-spatial store than when the path is complex. This observation is consistent with the Kemps (1999) report that the presence of structure has a facilitating effect on the temporary retention of visuo-spatial material, and lends sustenance to previous findings showing that the capacity of visuo-spatial working memory is limited by complexity (Kemps, 1999; Logie et al., 1990; Wilson et al., 1987).

The superiority for recall of structured over complex paths may also reflect the use of long-term knowledge. Research efforts within the verbal domain have provided empirical evidence for a contribution from long-term memory to the short-term retention of familiar words. For example, Gregg, Freedman, and Smith (1989) found greater spans for lists of high-frequency as opposed to low-frequency words, even when the mechanisms for speech coding had been removed through articulatory suppression. In the same vein, Hulme and colleagues (Hulme, Maughan, & Brown, 1991; Hulme, Roodenrys, Brown, & Mercer, 1995) reported lower memory spans for non-words than for words of various spoken lengths. In each case, a linear function related memory span to speech rate. The function for non-words had an equivalent slope, interpreted as reflecting a contribution from the phonological loop, but a lower intercept, interpreted as reflecting a contribution from long-term memory, than the function for words. Multhaup, Balota, and Cowan (1996) observed a similar relationship between the contribution from a phonological rehearsal process and long-term memory to span performance for words and non-words in both younger and older adults. Evidence from developmental studies further supports the role of long-term memory in verbal memory span. In addition to a developmental increase in articulatory speed, the familiarity of words (Henry & Millar, 1991; Roodenrys, Hulme, Alban, Ellis, & Brown, 1994) and the availability of

long-term memory representations (Roodenrys, Hulme, & Brown, 1993) are determining factors in age-related improvements in memory span.

In light of the hypothesised similarity between verbal and visuo-spatial working memory (Logie, 1995), an analogous line of reasoning could account for the results obtained in Experiment 1. The better performance on the structured paths may have benefited from the availability of pre-existing long-term memory representations for concepts expressing redundancy, such as symmetry, repetition and continuation. Complex paths presumably lack such representations in long-term memory. Hence, recall of structured paths may reflect the contribution from both short- and long-term memory mechanisms, i.e. the visuo-spatial sketch pad and long-term memory, whereas recall of the complex paths may reflect only a contribution from visuo-spatial working memory.

The observation of an increasing discrepancy in performance between the structured and the complex paths with increasingly longer block sequences lends sustenance to the idea of a long-term memory contribution to the serial recall of structured paths. The retention of short block sequences (three and four items) can be handled by the visuo-spatial slave system, and hence, did not yield differential recall scores for the structured and the complex paths. Recall of the longer sequences revealed a higher level of performance for the structured paths in comparison with the complex paths. In the case of structured paths, knowledge about the composition of the targeted block sequence may facilitate its retrieval. Even when the temporary representation of the to-be-remembered path stored in visuo-spatial working memory has decayed somewhat, as might be the case for sequences at supra-span level, the sequence can be reconstructed from partial information, provided it has representations in long-term memory. The extremely poor performance on the longer complex sequences suggests that retrieval of complex block sequences does not depend on other memory systems beside the visuo-spatial component of working memory. Memory span for such unstructured paths may thus provide a relatively pure measure of the operation of visuo-spatial working memory.

Experimental work on visuo-spatial suppression effects also implies a contribution from a long-term memory component to the temporary storage of visuo-spatial material. Visuo-spatial suppression attenuates visuo-spatial memory span, but does not eliminate the ability to retain a sequence of visuo-spatial items all together (e.g., Smyth et al., 1988; Smyth & Pendleton, 1989). Typically, span is reduced from approximately six or seven items to four or five items. So, even though the mechanisms for visuo-spatial coding in working memory have

been removed, a residual memory capacity remains. This residual performance may in part be attributable to the operation of a long-term memory store, analogous to the residual long-term memory contribution to verbal memory span under articulatory suppression (Craik, 1971; Gregg et al., 1989). The subsequent experiments aimed to provide empirical support for the potential involvement of a long-term memory system in the temporary retention of redundant movement sequences.

EXPERIMENT 2

Experiment 2 was designed to investigate whether the effect of complexity observed in Experiment 1 is purely a characteristic of visuo-spatial working memory, or whether it also involves the operation of a long-term memory mechanism. To this end, recall of structured and complex paths was combined with a concurrent visuo-spatial interference task. If visuo-spatial suppression removes the effect of complexity, then the discrepancy in span for the structured and the complex paths can be taken to reflect solely the operation of visuo-spatial working memory. However, if the effect of complexity remains under suppression, then the better performance on the structured paths as opposed to the complex ones is at least partially independent of differences in visuo-spatial short-term storage, and would thus argue for the involvement of long-term memory processes.

Method

Subjects and Design

Twenty first-year students at the Faculty of Psychology and Educational Sciences of the University of Ghent served as subjects. None of them had taken part in Experiment 1. Subjects were tested individually in a repeated measures design. The independent factors were path complexity (structured, complex) and suppression (control, spatial suppression). The order of the suppression conditions was counterbalanced across subjects.

Materials and Procedure

Materials for the blocks task were as for Experiment 1. The visuo-spatial suppression task consisted of the continuous sequential tapping task (Farmer et al., 1986). Subjects were

asked to repeatedly tap four metal plates (4 x 4 cm) positioned in a square pattern arrangement, with 2 cm between adjacent plates. They were instructed to work in a clockwise direction at a rate of approximately 2 to 3 taps per second.

The procedure for the blocks task was the same as in Experiment 1. In the dual-task condition, tapping was performed during presentation of the block sequences.

Results

A multivariate analysis was carried out with the average recall scores for each of the complexity x suppression conditions as the dependent variables. Mean data for each condition are shown in Table 1. The analysis revealed main effects of complexity, $F(1,19) = 40.85$, $P < .001$, and suppression, $F(1,19) = 74.56$, $P < .001$, but no interaction between these two factors, $F < 1$. Planned comparisons yielded a significant effect of complexity both for the control condition, $F(1,19) = 29.75$, $P < .001$, and under suppression, $F(1,19) = 26.01$, $P < .001$. Furthermore, in both conditions the difference in recall between the structured and the complex trials increased as a function of sequence length.

Insert Table 1 about here

Discussion

The results of Experiment 2 replicate those of Experiment 1 in that they yielded higher span scores for the structured paths than for the complex paths. Concurrent visuo-spatial suppression impaired recall, but did not abolish the effect of complexity. By analogy with the Gregg et al. (1989) study, it was thus shown that even when the mechanisms for visuo-spatial coding were eliminated, performance on the structured paths remained superior. It appears, then, that there are differences in memory span between structured and complex movement sequences that cannot be accounted for purely in terms of visuo-spatial working memory processes. The residual difference in recall suggests that the effect of path complexity may in addition be mediated by a long-term memory contribution. This finding indicates that the retrieval of the structured block sequences not only depends upon the operation of the visuo-spatial component of the working memory system, but may be aided by long-term memory

representations. Further empirical evidence is of course required to draw firm conclusions about this supplementary support from long-term memory.

Hulme et al. (1991) observed higher span scores for English words than for Italian words in English subjects. Recall of the English words reflected a contribution from both the phonological loop and long-term memory. The Italian words, however, were not represented in long-term memory. Hence, memory span for these words reflected only the operation of the phonological loop. Subsequent learning of their English translations created long-term memory representations for the Italian words, and increased memory span for them. A follow-up study (Hulme et al., 1995) extended these findings by demonstrating that familiarising subjects with the pronunciation of non-words improved their memory span.

Similarly, memory span for complex paths should also improve through learning, and would thus provide further support for a contribution from long-term memory to the temporary storage of structured block sequences. The question, however, remains as to whether this effect of learning would indeed reflect the creation of long-term memory representations, or rather an improvement in the acquisition of movement sequences in general. Experiment 3 was designed to explore these alternatives.

EXPERIMENT 3

Experiment 3 further investigated the role of long-term memory in the immediate recall of structured block sequences. For this purpose, subjects were trained on the complex paths. By analogy with the Hulme et al. (1991, 1995) studies, this should lead to an improvement in their recall because representations in long-term memory were created. Nevertheless, an interpretation in terms of general learning effects cannot be ruled out. To test for this possibility, performance was also assessed on a series of new complex paths. If learning is specific, in the sense that it is limited to those paths that were trained, this result would speak to the creation of long-term memory representations for these paths. This would then be a further indication that the short-term retention of structured block sequences is supported by long-term memory. However, if the effect of learning is not specific but transfers to other paths not previously encountered, then the increased span scores for the trained paths would instead point to a general improvement in the recall of unstructured block sequences.

Method

Subjects and Design

Twenty-six first-year students at the Faculty of Psychology and Educational Sciences of the University of Ghent took part in this experiment. None of them had participated in the previous experiments. Upon establishment of subjects' baseline performance in recall of structured and complex sequences, followed a training session in which subjects were trained on complex paths reproduced incorrectly. Subsequently, span performance for trained and new complex sequences was tested. To examine whether training would produce long-term learning effects, memory for the complex sequences was re-tested the following day.

Materials

Materials were as for Experiments 1 and 2.

Procedure

Initially baseline performance was determined. The procedure was the same as in Experiments 1 and 2. Visuo-spatial serial recall was assessed on structured and complex sequences. Subsequently, subjects were trained on the complex paths that were reproduced incorrectly. This training was based on a procedure devised by Hebb (1961). He presented subjects with digit lists just above span, whereby the same list was repeated every third trial, but the intervening lists were only shown once. As trials progressed recall of the repeated lists gradually improved, indicating that long-term memory representations of these lists had been created. Using the Corsi blocks task, Milner (1971) reported a similar increase in the recall of recurring visuo-spatial sequences.

The number of sequences trained varied across subjects, yet did not exceed a limit of nine sequences, so as to avoid fatigue. For each subject, training commenced with the shortest sequence that had previously not been recalled correctly, followed by the second shortest sequence and so forth until each erroneous sequence had been repeated in turn. Thereafter all sequences were shown again in the same order. Training was discontinued when each sequence had been repeated eight times. After a 15 min. break, in which subjects relaxed and listened to music, memory span for complex sequences was re-assessed. Subjects were presented with the same complex paths used in the assessment of baseline performance, some of which had now been trained, plus another 18 complex paths that were new. For subjects

initially assessed and subsequently trained on paths from set A, these new paths were the complex sequences from set B and vice-versa. Sequences were presented in a random order. Twenty-four hours later performance on the complex paths was tested again, using the same sequences as for the immediate test.

Results

The data were entered into a multivariate analysis with the average span scores for each of the six recall conditions (structured and complex sequences at baseline assessment, trained and new sequences at immediate test, and trained and new sequences at delayed test) as the dependent variables. The analysis of baseline performance yielded a significant effect of complexity, $F(1,25) = 37.94$, $P < .001$. Recall scores were higher for the structured sequences ($M = 5.71$, $SD = 0.71$) than for the complex sequences ($M = 4.74$, $SD = 0.56$). Compared to memory span for the complex paths at baseline assessment, performance on the trained sequences was better, both at immediate test, $F(1,25) = 34.78$, $P < .001$, and at delayed test, $F(1,25) = 32.56$, $P < .001$. In fact, training improved span for complex sequences up to a level attained on the structured sequences: $F < 1$ for the immediate test, and $F(1,25) = 2.88$, $P > .10$ for the delayed test. Recall of the new sequences at immediate test remained at the initial level of performance, $F < 1$. After a 24-hour delay, however, retention scores for these sequences were significantly higher than baseline performance of the complex paths, $F(1,25) = 7.62$, $P < .05$, and relative to their prior recall at immediate test, $F(1,25) = 7.92$, $P < .01$. Mean data of trained and new sequences at immediate and delayed test are shown in Table 2.

Insert Table 2 about here

Discussion

The results of Experiment 3 confirm the finding of the previous experiments that structured paths produced higher recall scores than complex paths. In line with previous studies (e.g., Hebb, 1961; Hulme et al., 1991, 1995; Milner, 1971), subsequent training of the complex paths improved memory span for them, virtually to the same level of performance initially observed for the structured paths. Effects of learning persisted even after a 24-hour delay.

Training of the complex paths led to an improvement in their span, either due to the creation of long-term memory representations, or due to a more general learning process. Performance at immediate test showed that learning was specific in that it did not transfer to new paths. This finding suggests that long-term memory representations were created for the trained paths, and thus provides further support for a long-term memory contribution to the temporary retention of structured block sequences. At delayed test, however, the effect of learning was no longer limited to the trained paths. Recall of the new paths now also significantly increased. This result suggests that the improvement in span observed for the trained paths may instead reflect an overall improvement in the acquisition of unstructured block sequences. These opposing results were tackled in the subsequent experiments.

Rather surprisingly the effect of learning did not transfer to new paths at first, but only became manifest second time around at delayed recall. Apparently an "incubation period" may be required for such transfer to occur. Alternatively, a single repetition of these new paths at immediate test may have been sufficient to create long-term memory representations for them, and subsequently produce learning effects at delayed test. The following experiments sought to clarify this controversy.

EXPERIMENT 4

The transfer hypothesis claims that the acquisition of new unstructured block sequences requires an "incubation period". According to the long-term memory representations hypothesis, however, one repetition suffices to create long-term memory representations, and hence, induce learning. Experiment 4 was designed to test the transfer hypothesis. This hypothesis states that if no immediate test had been administered in Experiment 3, recall of the new complex paths would still have increased at delayed test. Confirmation of the transfer hypothesis would support the view that the increase in span for the trained paths reflects a general learning process. As in Experiment 3, subjects were trained in the recall of complex block sequences. Twenty-four hours later, memory performance for trained and new complex sequences was tested.

Method

Subjects and Design

Twenty-eight first-year students at the Faculty of Psychology and Educational Sciences of the University of Ghent participated in this experiment. None of them had taken part in Experiments 1-3. Baseline performance was determined, followed by a training session. The following day, recall of trained and new complex sequences was assessed.

Materials and Procedure

Materials were the same as in Experiments 1-3. The procedure was as for Experiment 3, except that no immediate test was administered.

Results

The data were subjected to a multivariate analysis with the span measures obtained in each of the four recall conditions (structured and complex sequences at baseline assessment, and trained and new sequences at delayed test) as the dependent variables. Baseline performance revealed higher span scores for the structured sequences (M = 5.63, SD = 0.84) than for the complex sequences (M = 4.75, SD = 0.70), $F(1,27) = 32.01$, $P < .001$. Span performance significantly improved for the trained sequences (M = 5.43, SD = 0.68), $F(1,27) = 25.80$, $P < .001$, close to the level of recall obtained on the structured trials, $F(1,27) = 2.03$, $P > .15$. Recall of the new sequences (M = 4.91, SD = 0.73), however, remained at the initial low level, $F(1,27) = 1.20$, $P > .25$.

Discussion

The results obtained in Experiment 4 strengthen the finding of the previous experiments that immediate recall of block sequences is determined by the structure of the to-be-remembered path. Subsequent training of the complex paths again improved their span, up to a level similar to the structured paths. Memory for the new complex paths, however, remained at the initial level of performance, showing that learning did not transfer to other paths. The latter observation clearly falsifies the transfer hypothesis: In the absence of an immediate test, recall of new complex paths did not increase after a 24-hour delay. From this it can be concluded that the increase in span for the trained paths cannot be ascribed to a general learning process.

Instead, the data support the idea of specific learning effects, and hence, confirm the assumption that training subjects in the recall of complex paths leads to the creation of long-term memory representations for these particular paths, which in turn results in an improvement in their memory span, both immediately (Experiment 3) and after delay (Experiments 3 and 4). This encourages the notion of a long-term memory contribution to the recall of structured block sequences. Moreover, these results show that the increase in performance on the new paths at delayed recall in Experiment 3 was not due to an "incubation period". Instead they lend sustenance to the claim that a single repetition at immediate test may have been sufficient to induce learning. This possibility was studied in greater detail in Experiment 5.

EXPERIMENT 5

Experiment 5 was designed to test the long-term memory representations hypothesis. According to this hypothesis, a single repetition is sufficient to create representations in long-term memory for recurring block sequences, and thus induce learning. This would make a training session comprising several repetitions redundant. Confirmation of the long-term memory representations hypothesis would offer additional support for the notion that the increase in recall for trained paths reflects the creation of long-term memory representations.

Method

Subjects and Design

Fifty-six first-year students at the Faculty of Psychology and Educational Sciences of the University of Ghent participated as a course requirement. None had taken part in the previous experiments. Subjects' baseline performance for structured and complex sequences was assessed. Recall of old and new complex sequences was tested both immediately and after a 24-hour delay. To avoid confounding these two times of test (cf. Experiment 3), this factor was manipulated between groups. Thus twenty-eight subjects were given an immediate test; the remaining twenty-eight were tested the following day. Subjects were randomly assigned to groups.

Materials and Procedure

Materials were as for the previous experiments. The procedure was broadly the same as in Experiments 3 and 4, except that there was no training session. In consistency with Experiment 3, subjects in the immediate test condition were given a 15 min. break upon assessment of baseline performance. Subsequently, memory span for old (i.e., used to determine baseline performance) and new complex sequences was tested, analogous to the procedure employed in Experiments 3 and 4. For subjects in the delayed test condition, baseline performance was determined in the first session. Assessment of old and new complex sequences was postponed till the next day.

Results

To test for an effect of time of test, a multivariate analysis was performed with time of test as between-subjects factor. The retention scores obtained in each of the four recall conditions (structured and complex sequences at baseline assessment, and old and new sequences at test) were the dependent variables. Hypotheses were tested by means of contrasts in the independent and dependent variables. Mean data are shown in Table 3. There was no effect of time of test, nor did this factor interact with any of the recall conditions ($F < 1$).

To examine the effect of learning, the data of the two time of test conditions were subjected to separate multivariate analyses with the average span scores in each of the four recall conditions (structured and complex sequences at baseline assessment, and old and new sequences at test) as the dependent variables.

Insert Table 3 about here

Immediate Test

Baseline performance yielded an effect of complexity, $F(1,27) = 51.27$, $P < .001$. Memory scores for the (old) complex sequences were significantly higher at second presentation, $F(1,27) = 10.83$, $P < .01$, though not quite up to the level observed for the structured paths, $F(1,27) = 8.90$, $P < .01$. Recall of the new complex sequences remained at the initial level of performance, $F < 1$.

Delayed Test

Analysis of baseline performance revealed an effect of complexity, $F(1,27) = 47.68$, $P < .001$. Span scores for the (old) complex sequences were significantly higher the following day, $F(1,27) = 10.55$, $P < .01$, but did not reach the level of recall obtained on the structured trials, $F(1,27) = 24.84$, $P < .001$. Recall of the new sequences, however, remained at the initial level of performance, $F < 1$.

Discussion

The data reported here reinforce the results of the previous experiments in that they revealed an effect of path complexity at baseline performance. Recall of the old complex sequences was found to have increased at test. The lack of an effect of time of test indicates that span performance improved to the same extent in the immediate and delayed assessment conditions. It follows that one repetition suffices to induce (long-term) learning effects. The effect of learning did not transfer to new sequences, so that a general learning effect can be ruled out. These results can be interpreted as showing that long-term memory representations were created for the recurring sequences on the basis of a single repetition. This strengthens the argument that the increase in recall of new complex paths observed at delayed recall in Experiment 3 was due to the creation of representations in long-term memory, brought on by one prior presentation at immediate test. It is clear from the data reported here that the improvement in span for trained paths, found in Experiments 3 and 4, was due to the creation of representations for these paths in long-term memory. Together, these findings lend further support to the availability of long-term memory representations for the structured paths.

Although a single repetition of a sequence of movements clearly yields an improvement in visuo-spatial memory span, the effect of learning is more substantial after several repetitions. In Experiments 3 and 4 training of the complex sequences increased their recall, comparable to the level observed for the structured sequences. In this experiment one prior repetition of the old complex sequences also improved memory span for them, but no where near the level of performance attained on the structured paths. The effect of learning is, however, equally durable, regardless of the number of repetitions. In Experiments 3 and 4 training produced long-term learning effects. Similarly, in the present experiment the effect of learning persisted over a longer period of time after just one repetition.

GENERAL DISCUSSION

The experiments provide further information about the processes involved in visuo-spatial short-term retention. The complexity of the presented paths was consistently shown to have an effect on immediate visuo-spatial recall. Structured paths clearly facilitated span performance, and hence, supports and extends the Kemps (1999) finding that structural complexity is a salient feature of short-term visuo-spatial storage. Redundant paths contain less information than complex paths, because one part is dependent upon or determined by another. Encoding and maintenance of a structured path therefore consumes less storage capacity of the visuo-spatial working memory system. This observation is consistent with results reported by previous studies showing that visuo-spatial short-term memory is limited by complexity (Kemps, 1999; Logie et al., 1990; Wilson et al., 1987). This interpretation gains further support from findings reported by Zoelch and Schumann-Hengsteler (1999). Using the original nine-block Corsi display, they too found an effect of path complexity. In their study, path complexity was defined in terms of the metric length of the path, the number of barriers within the path, the number of crossings within the path, and the shape produced by the path.

It is conceivable that the retrieval of structured paths was supported by long-term knowledge. When the presented path constitutes some form of redundancy, knowledge about its composition can be used to reconstruct the targeted block sequence, even if its temporary representation held in visuo-spatial working memory has partially decayed, this in contrast to a complex path. The superior recall of the structured paths may therefore reflect a contribution from long-term memory. Several observations in fact point to the involvement of long-term memory processes in the recall of structured block sequences. First, visuo-spatial suppression did not remove the effect of complexity. Even when the mechanisms for visuo-spatial coding had been eliminated, span scores were still higher for structured as compared to complex block sequences. Further support for a long-term memory contribution as explanation for the difference in recall between the structured and the complex block sequences comes from the effects of training subjects in the recall of complex sequences. This led to the creation of long-term memory representations for these sequences, as shown by an improvement in their span, in the absence of such an effect for new sequences.

The effect of teaching subjects a sequence of movements revealed three basic characteristics. First, the effect of learning is specific. Learning was limited to those

sequences that had been trained; it did not transfer to other paths. Second, the effect of learning does not require extensive training. One repetition was sufficient to produce learning. Third, the effect of learning is a long-term effect. Learning persisted over a 24-hour retention interval.

It is clear from the pattern of results obtained that memory span for structured block sequences involves the contribution from two mechanisms: a limited capacity short-term visuo-spatial storage system and a long-term memory component. This interpretation is consistent with Phillips and Christie's (1977) suggestion of a long-term memory contribution to visual recognition memory for matrix patterns. Subjects' memory for sequences of matrix patterns was probed. Recognition performance was excellent for the final pattern, but just above chance for the other serial positions. Phillips and Christie suggested that the one-item recency effect reflects the operation of visual short-term memory, whereas the earlier patterns are retained in long-term memory.

The idea of a long-term memory contribution to the serial recall of structured block sequences fits well with Logie's (1995, 1996; Beschin, Cocchini, Della Sala, & Logie, 1997; Ellis, Della Sala, & Logie, 1996) modified notion of working memory as a cognitive workspace for storing and manipulating long-term memory representations, rather than as a gateway between sensory input and long-term memory. Within this view, access to working memory can only be via stored knowledge in long-term memory, not directly from the environment. The perceptual input of a structured path therefore activates representations in long-term memory for concepts expressing redundancy, such as symmetry, repetition and continuation, before it enters visuo-spatial working memory for further processing. Hence, storage and retrieval of structured block sequences implies an interaction between the visuo-spatial sketch pad and long-term memory. Complex paths, however, lack long-term memory representations. The perceptual input of such a path would not benefit from accessing long-term memory, and thus presumably gains direct entry to the visuo-spatial temporary store. Consequently, recall of complex block sequences reflects only the operation of the visuo-spatial slave system.

The use of a training procedure analogous to the methodology employed by Hulme et al. (1991, 1995) does not a priori assume any similarity in the underlying cognitive processes of the effect of word familiarity in verbal memory and the effect of path complexity in visuo-spatial memory. It serves merely as a research strategy aimed at detecting the mechanisms underlying the limits of visuo-spatial memory span. The effect of word familiarity on verbal

span is not a characteristic of the phonological loop, but is attributable solely to the operation of long-term memory. In contrast, the data reported here seem to suggest that the effect of path complexity on visuo-spatial span may reflect the operation of both short- and long-term memory processes. This of course remains to be verified. Unfortunately, the respective contribution of these mechanisms can at present not be quantified. In the verbal domain, the time-based articulatory rehearsal process reflects the contribution of the phonological loop to memory span. (Hulme et al., 1991, 1995; Roodenrys et al., 1993). Speech rate provides an adequate measure of subvocal rehearsal. There is, however, no measure by which to estimate the contribution of the visuo-spatial sketch pad to short-term recall. No underlying rehearsal mechanism has as yet been found in visuo-spatial working memory (Smyth & Scholey, 1992, 1994). Therefore, the evidence for a long-term memory contribution to the temporary retention of structured visuo-spatial material remains limited.

Thus, before drawing firm conclusions, possible alternative interpretations of the data should be considered. For example, it is conceivable that redundancy induced through structuring merely reduces the amount of information to be encoded, in which case the effect of path complexity would be attributable to the operation of basic perceptual processes. However, in light of the implications for the role of long-term memory representations in the temporary retention of structured movement sequences presented here, any contribution from perceptual sources cannot be but partial. Clearly, further investigation is warranted to specify the mechanisms that mediate the effects of redundancy on visuo-spatial short-term storage.

Another avenue for further exploration pertains to the nature of the long-term memory contribution inferred from the experiments reported here. Hulme et al. (1995) demonstrated that the contribution from long-term memory to verbal memory span is phonological in nature, rather than lexical or semantic. The present work can as yet provide no insight into the relevant long-term memory representations in the visuo-spatial domain. No doubt it is the visual and spatial properties of representations encoded in long-term memory that are important in supporting the temporary retention of movement sequences. To the extent that the characteristics of these representations can be further delineated, it should be possible to describe the mechanisms through which long-term memory has its effect on short-term visuo-spatial memory. A related issue concerns the locus of this long-term memory effect. Hulme et al. (1997) showed that the contribution from long-term phonological representations to immediate verbal recall occurs during the process of redintegration (i.e., reconstruction of a to-be-recalled item from degraded short-term memory traces) at retrieval. The facilitation

from long-term memory in the current study is also believed to be at recall. It was argued that representations in long-term memory were consulted in the process of retrieving structured block sequences from visuo-spatial working memory. However, with reference to the idea that the contents of working memory are derived from the activation of long-term memory traces (Beschin et al., 1997; Ellis et al., 1996; Logie, 1995, 1996), the potential for a long-term memory effect at encoding cannot be ruled out. It is clear that continued examination is warranted in order to pinpoint the contribution from long-term memory to visuo-spatial short-term retention. Furthermore, the logic of this study was driven by the assumption that the long-term memory representations that are invoked to assist recall of the structured block sequences are essentially the same as those that are built up for the unstructured sequences through training. This view is of course subject to empirical verification.

The present results support the claim that complexity is an important characteristic of short-term visuo-spatial storage. In particular, memory for block sequences would seem to be determined by a) the number of blocks on the board, b) the structure of the display, and c) the structure of the to-be-remembered path. These measures of complexity may, however, load different components of the cognitive system. Unlike the complexity induced by the path, the measures of complexity inherent to the display do not as readily imply the operation of a long-term memory component. Further, the display of blocks is static, whereas the path consists of a sequence of movements that are constructed step by step. Maintenance of the display receives external support. Storage of the path requires active processing. In terms of Logie's (1995) dual-component architecture of visuo-spatial working memory, the representation of the display may be stored in the passive visual cache, whereas the representation of the path is "rehearsed" by the inner scribe. Further research is required to clarify this speculative link between the effects of complexity and the distinction between a visual buffer and a spatial rehearsal function.

In conclusion, the amount of visuo-spatial material that can be retained for short-term recall is determined by several measures of both quantitative and structural complexity. This multifaceted construct offers a potential technique for elucidating the precise nature of the mechanisms underlying visuo-spatial short-term retention.

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AUTHOR'S NOTE

Requests for reprints should be sent to Eva Kemps, Department of Experimental Psychology, University of Ghent, Henri Dunantlaan 2, B-9000 Ghent, Belgium. E-mail: Eva.Kemps@rug.ac.be

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TABLE 1

Memory Span as a Function of Complexity and Suppression in Experiment 2 (Standard Deviations in Brackets)

	Structured	*Complex*
Control	5.83 (0.91)	4.98 (0.73)
Suppression	5.06 (0.98)	4.11 (0.53)

TABLE 2

Average Recall Scores for Trained and New Complex Paths at Immediate and Delayed Test in Experiment 3 (Standard Deviations in Brackets)

	Trained	*New*
Immediate Test	5.59 (0.79)	4.84 (0.67)
Delayed Test	5.47 (0.64)	5.11 (0.64)

TABLE 3

Baseline and Test Performance in Experiment 5 (Standard Deviations in Brackets)

	Baseline Performance		*Test Performance*	
	Structured	*Complex*	*Old*	*New*
Immediate Test	5.77 (0.82)	4.93 (0.71)	5.31 (0.70)	4.96 (0.59)
Delayed Test	5.84 (0.83)	4.76 (0.50)	5.14 (0.65)	4.81 (0.62)

FIGURE CAPTIONS

1. Examples of block sequences used in Experiments 1 to 5. Sequence (a) is symmetric and continuous; sequence (b) elicits symmetry and repetition; sequences (c) and (d) are unstructured.
2. Average number of block sequences correctly recalled as a function of complexity and sequence length in Experiment 1.

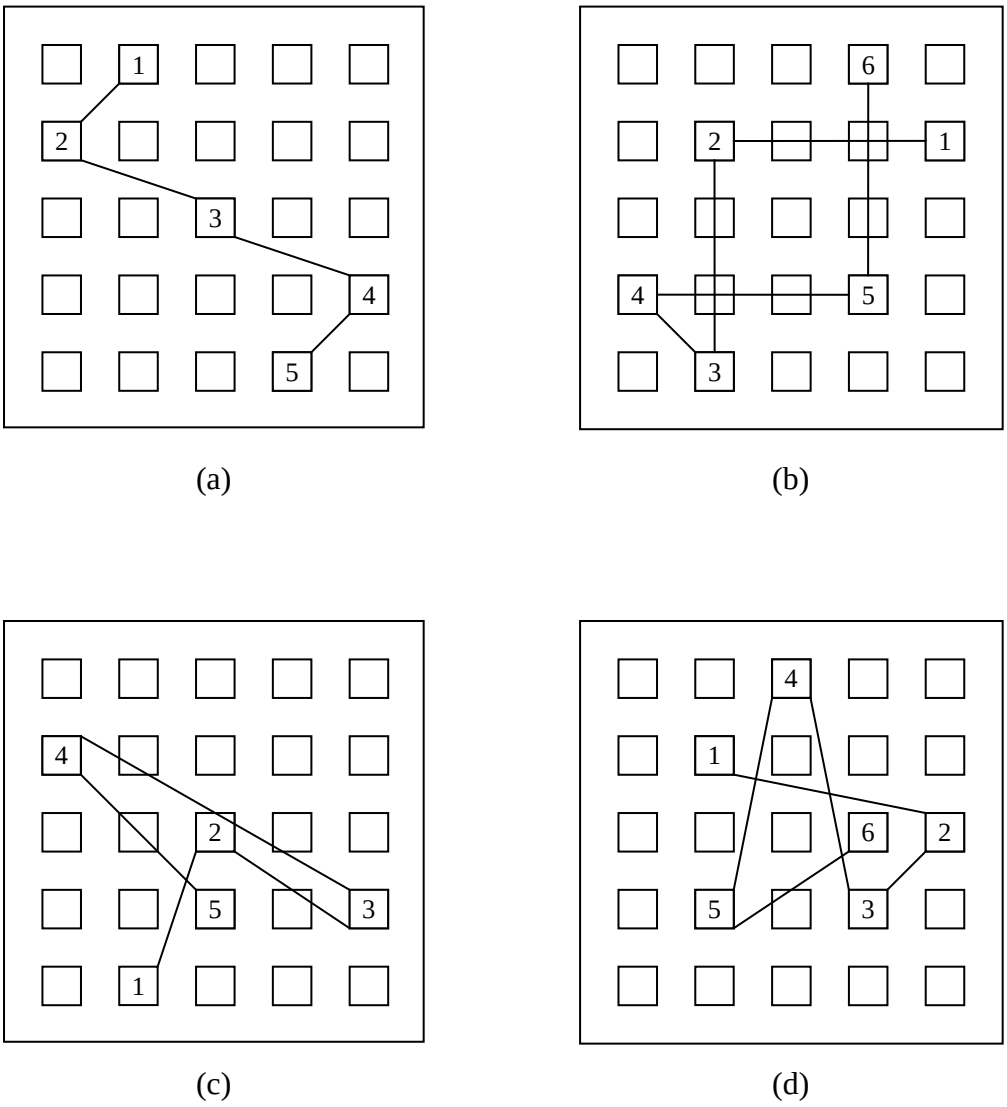
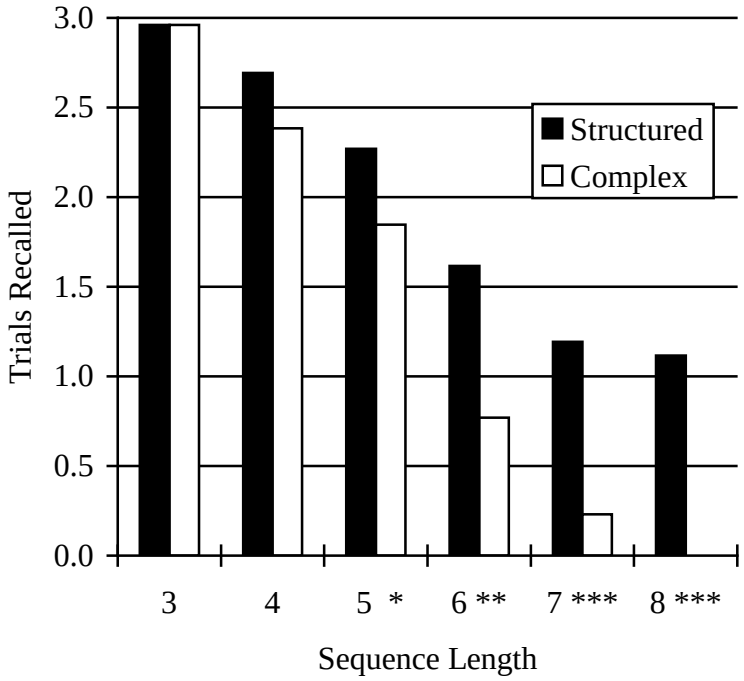


FIG. 1.



* $p < .05$ ** $p < .01$ *** $p < .001$

FIG. 2.