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Effects of Complexity on Visuo-spatial Working Memory

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ABSTRACT

Four experiments are reported in which the effect of complexity on short-term retention of visuo-spatial material was explored. The determinants of complexity can be separated into a quantitative factor, which sets an upper bound on complexity, and a structural factor, which reduces complexity. Variants of the Corsi blocks task were administered across the various experiments. Quantitative complexity was manipulated through the number of blocks on the board. Structural complexity was induced through the positioning of the blocks. Visuo-spatial span was found to be susceptible to both measures of complexity. Performance was inversely related to the number of blocks. Recall was also better when the blocks were positioned in a matrix than in a random fashion. Moreover, the effect of complexity was shown to be moderated by an interaction between structure and amount of information presented. These results demonstrate that complexity is an important characteristic of visuo-spatial working memory. This phenomenon may be used to further explore the properties of the visuo-spatial sketch pad, and advance its theoretical development.

INTRODUCTION

Due to a lack of appropriate techniques for its investigation, insight into the nature of the visuo-spatial sketch pad (VSSP) has been overshadowed by the theoretically more sophisticated phonological loop (PL). During the last decade, however, investigation of the characteristics of visuo-spatial working memory has benefited from research efforts within the working memory framework (Baddeley & Hitch, 1974). For instance, the VSSP has been shown to operate independently from the PL (e.g. Logie, Zucco, & Baddeley, 1990) and to be susceptible to both visual and spatial interference (e.g. Baddeley, Grant, Wight, & Thomson, 1975; Logie, 1986). Several studies have demonstrated a close link between spatial coding and movement control (e.g. Quinn, 1994; Smyth, Pearson, & Pendleton, 1988). Furthermore, visually presented material has been found to gain obligatory access to a temporary visual store (Logie, 1986; Quinn & McConnell, 1996).

Logie (1989, 1995) suggests that the assumption of an analogous approach to the one used for studying the PL may provide a useful methodological framework for the further exploration of the VSSP. The development of the PL has been successful as a result of converging evidence from a number of robust phenomena associated with verbal short-term memory, i.e. effects of phonological similarity (Conrad, 1964), unattended speech (Salamé & Baddeley, 1982), word length (Baddeley, Thomson, & Buchanan, 1975) and articulatory suppression (Levy, 1971).

Evidence from visual recency effects (Broadbent & Broadbent, 1981; Phillips & Christie, 1977a, 1977b; Walker, Hitch, & Duroe, 1993), visual confusion errors (Frick, 1985; Hue & Erickson, 1988; Wolford & Hollingsworth, 1974), and the temporary retention of movements (Quinn, 1994; Quinn & Ralston, 1986; Smyth et al., 1988) have led Logie to postulate a dichotomy in the VSSP, analogous to the PL. He suggests that the VSSP also comprises two separate though complementary subsystems: a passive visual temporary store (visual cache) and an active spatially based rehearsal mechanism (inner scribe). The visual cache is thought to be involved in the temporary retention of visual information, such as patterns and colours. The inner scribe is assumed to be responsible for the planning and control of movements.

The aim of this study is to cast some light on the characteristics of visuo-spatial short-term retention, based on a possible counterpart to the word length effect in visuo-spatial memory span. The number of items that can be retained in immediate verbal memory is determined by the length of time it takes to articulate them. This effect reflects the time-limited capacity of the articulatory rehearsal process, which allows more short words than long ones to be rehearsed, and hence recalled.

In an initial attempt to find a visuo-spatial analogue to the word length effect, Smyth and Scholey (1994a) employed a two-dimensional computerised display of the Corsi blocks task. The size of the blocks and the distance between them were varied to manipulate movement time by hand or eye. The expected relationship between the time taken to make movements to spatial targets and the number of locations that can be recalled was not found. As such, no evidence could be provided for a covert visuo-spatial rehearsal system linked to overt responding, analogous to the way subvocal rehearsal is related to speech rate in verbal span.

The further exploration of an analogue to the word length effect in the visuo-spatial domain first and foremost requires an adequate measure of the notion ‘visuo-spatial length’. The concept of complexity offers a distinct possibility. Using a visual matrix span task, Wilson, Scott and Power (1987) demonstrated that complex patterns are retained less well than simple patterns. On each trial subjects were given a matrix pattern with half of the cells filled randomly. Subsequently it was removed and replaced with a similar pattern in which one of the previously filled cells was left blank. Subjects had to indicate which cell had been changed. The complexity of the patterns was raised over trials by increasing the total number of cells in the matrix, following a classic span procedure. Subjects could recognise which item had been changed out of 14 spatial locations within a pattern. In a more recent paper, Logie et al. (1990) employed the visual memory span procedure in a dual task paradigm. Performance was again found to be limited by the complexity of the matrix patterns. In addition, span was disrupted by a concurrent visuo-spatial task, but not by a secondary verbal task. These findings provide evidence that the capacity of the VSSP is limited by pattern complexity.

In the previously mentioned studies complexity was operationally defined as the number of pattern elements in a matrix. However, stimuli do not vary only in terms of number of elements, but also in the nature of the elements. Over the years complexity has been given a wide range of definitions, and researchers have employed the most diverse measurements of the concept. According to Berlyne (1960) complexity basically refers to the amount of variety in a stimulus. For instance, the complexity of a stimulus may be defined by the number of distinguishable elements, the similarity between elements, or the degree to which several elements are perceived as an entity.

The concept of complexity is also closely linked to the Gestalt principle of “figural goodness”. Gestalt factors such as similarity, symmetry, continuation, simplicity, closure, proximity, homogeneity and other forms of regularity all contribute to pattern goodness, and thus reduce complexity. Within the framework of information-theory (Attneave, 1954), a good gestalt is defined in terms of redundancy. For example, a symmetrical pattern constitutes a high degree of internal redundancy in the sense that one portion is dependent upon or determined by another, and that it contains less information than an asymmetrical figure. Several studies have found recall errors of dot patterns to be a linear function of degree of symmetry and amount of information (Attneave, 1955; Schnore and Partington, 1967). Complexity is related to the inverse of redundancy. Complex figures lack interdependencies among their parts. Therefore, they can assume a greater range of alternative forms, and are consequently associated with more uncertainty.

Complex visual objects are not only more difficult to reproduce from memory (Attneave, 1955; Ichikawa, 1982), but also harder to recognise (Perkins, 1932; Vanderplas & Garvin, 1959), and to discriminate among similar figures (Adams, Fitts, Rappaport, & Weinstein, 1954) than simple ones. Complex figures are remembered less accurately, because they are encoded into a more complex form.

In a series of experiments on perceived complexity of matrices, Chipman (1977) showed that the various operational definitions of the concept of complexity found within the literature can essentially be reduced to two dimensions: a quantitative one and a structural one. The complexity of a stimulus varies with pattern quantity on the one hand and with the degree to which its constituent parts are organised on the other. Results of both factor and multiple regression analyses in a study by Ichikawa (1985) on judgements of pattern complexity provided further support for the proposition of a conceptual distinction between a quantitative and a structural factor underlying complexity. Pattern quantity sets an upper bound value for complexity, which is reduced by the presence of relevant organisation. The quantitative variable comprises features such as the number of elements in a pattern, size of elements and proximity of elements. Structured patterns are those in which a relationship exists between its parts, e.g. symmetry, repetition and rotation, and are thus said to be redundant. Therefore, the measure of complexity employed in the Wilson et al. (1987) and the Logie et al. (1990) studies may be considered a quantitative measure of complexity.

The purpose of the following experiments was to further explore the effect of complexity on visuo-spatial short-term retention. More specifically, the influence of both quantitative and structural measures of complexity on visuo-spatial memory span was studied. A clear demarcation of these two components of complexity should render some clarity into the characteristics of the VSSP. In each of the experiments a variant of the Corsi blocks task was used. This task has frequently been employed to assess visuo-spatial short-term memory (e.g. De Renzi & Nichelli, 1975; Milner, 1971; Orsini et al., 1986; Smyth & Scholey, 1992, 1994a, 1994b) and has been shown to reflect the operation of the VSSP (Hanley, Young, & Pearson, 1991). To investigate the effect of the quantitative component of complexity the number of blocks on the board was varied. To examine the effect of structural characteristics of complexity the positioning of the blocks was manipulated.

Due to its construction the Corsi blocks task itself elicits two kinds of (structural) complexity: the complexity inherent to the display and the complexity of the to-be-remembered span. The display is constantly present, whereas the path is constructed bit by bit during presentation. Therefore, more external support is provided for recall of structure manifested by the display than by the path. As a result, the processing of the representations of the respective types of complexity may, at least in part, require different cognitive resources. The display entails a simultaneous, visual, static presentation of complexity. The path, however, consists of a sequence of movements, and thus constitutes a sequential presentation of complexity. The former involves a spatial representation; it pertains to the spatial relationship among items. The latter is related to the successive order of items, and implies a temporal representation. To avoid confounding the two kinds of different yet interrelated structural complexity, the present study focused only on the simultaneous complexity of the display.

A related issue was addressed by Smirni, Villardita and Zappala (1983). They demonstrated that visuo-spatial memory performance on the Corsi blocks task did not only depend on the length of the to-be-remembered path, but also on the specific digit sequence of the path. The latter was found to generate different spatial configurations for a given path length. Presenting sequences of homogeneous difficulty reduced this effect of differential spatial patterns evoked by digit sequence. However, unlike the original Corsi blocks procedure, Smirni et al. (1983) presented a particular block more than once per trial. To minimise the influence of complexity of the path and to resolve the problem of presenting trials of heterogeneous difficulty in the present study, different versions of the task were constructed.

Four experiments were designed to explore the limitations on visuo-spatial short-term storage in terms of structural and quantitative complexity. Experiment 1 tackled the issue of structural complexity. In Experiment 2 quantitative complexity was added to the design.

Experiments 3 and 4 explored the effect of quantitative complexity in further detail, in interaction with structural complexity.

EXPERIMENT 1

Experiment 1 addressed the effect of structural complexity on the temporary retention of visuo-spatial material. Structural complexity was manipulated by mounting the blocks on three displays varying in degree of structure: a structured display, a semi-structured display and a random display. It was hypothesised that visuo-spatial memory span would be proportionate to the degree of structure manifest in the display.

Method

Subjects and Design. Thirty 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 structure of the display. The order in which the conditions were administered was counterbalanced across subjects.

Materials. The apparatus for the original Corsi blocks task consists of a set of nine identical black square blocks arrayed in a quasi-random pattern on a black wooden board. All three displays used here consisted of nine blocks (4 x 4 x 4 cm) positioned on a 30 x 30 cm board. The structured display constituted a regular 3x3 matrix. The semi-structured display was adopted from a pattern employed by Berlyne (1958) in a study on complexity and redundancy. This display was considered semi-structured, because it reveals a metrical configuration. Unlike the random display, the blocks of the semi-structured display are neatly arranged in imaginary rows and columns resembling a 5x5 matrix with only nine cells filled. The random display was the traditional Corsi block display. Two-dimensional outlines of the displays are shown in Fig. 1. To facilitate presentation and scoring, the sides of the blocks facing the experimenter were numbered from 1 to 9; these numbers were not visible to the subject.

Insert Fig. 1 about here

Procedure. Subjects were tested individually in a quiet room. Instructions about the task were given, followed by a brief practice session. The experimenter tapped out a particular sequence of blocks at a rate of one per second; the subject was required to touch the same blocks in their order of presentation immediately afterwards. Three trials were given at each sequence length, beginning with trials of three items. If two out of three sequences were repeated correctly, the sequence length was increased by one. When the subject failed on two trials of a given length testing was discontinued. No block occurred more than once per trial. Visuo-spatial span was calculated by adding the length of the three longest sequences which the subject recalled correctly, and dividing this sum by three.

Three sets of visuo-spatial sequences were randomly constructed. These were counterbalanced over the three conditions.

Results

In accordance with suggestions formulated by McCall and Appelbaum (1973) for the analysis of repeated measures designs, the average span scores were subjected to a multivariate analysis[1]. There was a main effect of structure [$F(2,28) = 12.02$, $P < 0.001$]. Mean level of performance was 6.38 (SD = 0.72) in the structured display, 5.92 (SD = 0.82) in the semi-structured display, and 5.82 (SD = 0.77) in the random display. Planned comparisons yielded significant differences in performance between the matrix and the semi-structured display conditions [$F(1,29) = 11.89$, $P < 0.01$], and between the matrix and the random display conditions [$F(1,29) = 19.12$, $P < 0.001$]. The semi-structured and the random displays, however, did not differ from one another ($F < 1$).

Discussion

Recall of a series of spatial targets was shown to be determined by the structural complexity of the to-be-remembered material. Memory performance was better when the blocks portrayed a matrix than a random display. This result suggests that structured information consumes less storage capacity of the visuo-spatial system than unstructured material. Rather surprisingly recall was no better on the semi-structured display than on the random. Perhaps the structure elicited by the semi-structured display was not sufficiently salient, and hence, too difficult for subjects to be detected. There are indeed suggestions in the literature that not all kinds of structure are equally effective (e.g. Fitts, Weinstein, Rappaport, Anderson, & Leonard, 1956). Alternatively, the structure in the semi-structured display may not have provided any additional support to memory. Yet another explanation could be that subjects perceived the semi-structured display as a 5x5 matrix with nine cells randomly filled, so that a quantitative factor may be of importance in this condition.

EXPERIMENT 2

Experiment 2 was designed to investigate the effect of quantitative complexity on the retention of visuo-spatial information. Quantitative complexity was operationally defined in terms of the number of blocks on the board. Three displays with respectively 9, 16, and 25 blocks were used. To test for a possible interaction between quantitative and structural measures of complexity, the structure of the display was also taken into account. Bearing in mind the non-differential results between the semi-structured and the random displays of the previous experiment, only a matrix and a random display were included. The hypothesis was that visuo-spatial serial recall would be inversely related to the number of elements in the display, in both the matrix and the random display conditions.

Method

Subjects and Design. Forty-eight 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 experiment. Subjects were randomly assigned to the conditions of a 2 (display: matrix versus random) x 3 (number of blocks: 9, 16 and 25) factorial design with repeated measures on the last factor. The order of the conditions was counterbalanced over subjects.

Materials and Procedure. All three matrix displays were arranged on a square board (40 x 40 cm). The overall size of the displays was equal. As a result, the average distance between the blocks on the 3x3 matrix used here was larger than in the matrix condition of Experiment 1. In addition, the average distance between the blocks on the 3x3 matrix (9 blocks) was larger than between those on the 4x4 matrix (16 blocks), which in turn was larger than between those on the 5x5 matrix (25 blocks). However, performance should not be affected by these variations in distance. As noted previously, Smyth and Scholey (1994a) showed that varying the distance between blocks had no effect on span. In each of the random displays the blocks were arrayed on a 40 x 50 cm board. The positions of the additional blocks were in part adopted from Smyth and Scholey (1996) and are shown in Fig. 2. Again the average distance between blocks decreased with an increasing number of blocks.

In each condition the total number of blocks on the board was taken into account in the construction of the to-be-presented sequences. For all three levels of the factor "number of blocks" two sets of sequences were constructed at random. These were counterbalanced over the two display types. The procedure was as for Experiment 1.

Insert Fig. 2 about here

Results

The data were entered into a multivariate analysis with the structure of the display as between-subject factor and the span measures obtained in each of the three number of blocks conditions as the dependent variables. Hypotheses were tested by means of contrasts in the independent and dependent variables. Mean data for each condition are shown in Table 1.

Insert Table 1 about here

The analysis revealed main effects of number of blocks [$F(2,45) = 46.09$, $P < 0.001$] and structure [$F(1,46) = 5.33$, $P < 0.05$]. There was also an interaction between these two variables, [$F(2,45) = 4.06$, $P < 0.05$]. Planned contrasts demonstrated that performance was better on a display with 9 blocks than with both 16 [$F(1,46) = 23.51$, $P < 0.001$] or 25 blocks [$F(1,46) = 92.32$, $P < 0.001$]. Recall scores were also reliably higher with 16 blocks than with 25 [$F(1,46) = 27.12$, $P < 0.001$]. The matrix produced superior results in comparison with the random display when 9 [$F(1,46) = 15.29$, $P < 0.001$] or 16 blocks [$F(1,46) = 6.05$, $P < 0.05$] were used, but not with 25 blocks ($F < 1$).

Separate analyses of variance for the two display types yielded a decrease in span scores with an increasing number of blocks, in both the matrix [$F(2,22) = 31.82$, $P < 0.001$] and the random display condition [$F(2,22) = 15.07$, $P < 0.001$]. Moreover, all pair-wise contrasts among the three levels of the factor "number of blocks" were significant, for the matrix ($0.01 < P < 0.001$) as well as the random display ($0.05 < P < 0.001$).

Discussion

The data reported here confirm the finding of Experiment 1 that recall scores were higher when the blocks were positioned in a matrix than in a random fashion. However, the superiority of the matrix display diminished with an increasing number of blocks. In fact, when 25 blocks were used the two displays were not different from each other. Apparently, the presence of structure in the display does not provide additional support with a larger number of items. This suggests that the effect of structural complexity may be secondary to the effect of quantitative complexity on the short-term retention of visuo-spatial material.

In addition, both displays produced differential span scores as a function of number of blocks. Discriminating a set of targets among a number of items seems to make higher demands on the cognitive system with an increasing number of items. This result lends sustenance to the Wilson et al. (1987) and Logie et al. (1990) findings that visuo-spatial short-term memory is limited by the complexity of the visuo-spatial material, i.e. in terms of the number of elements in a stimulus. The data are also consistent with work by Vecchi and Logie (personal communication), who compared visuo-spatial memory span on a 3x3 matrix (9 blocks) with a 5x5 matrix (25 blocks). Performance on the 3x3 matrix was better than on the 5x5. This result was attributed to the differential visual complexity of the displays.

Furthermore, the decrease in span scores with an increasing number of blocks implies that the rehearsal mechanism was not reduced to the targeted positions. Although subjects did not have to retain the positions of all the blocks, the total number of blocks did come into effect. Moreover, the fact that for a given condition the total number of blocks on the board was fixed and constantly remained on display did not provide sufficient external support. Perhaps if only a subset of the total number of blocks on the display were relevant, the rehearsal mechanism may be limited to those relevant blocks. This issue was addressed in Experiment 3.

Finally, it is clear from Table 1 that the average level of performance on the two displays with nine blocks is similar to the results obtained in the respective conditions of Experiment 1. Given that the blocks were mounted on a larger board in this experiment and thus positioned further apart, this observation supports and extends the Smyth and Scholey (1994a) finding that visuo-spatial span is not affected by distance between items.

EXPERIMENT 3

Experiment 3 tested the hypothesis that the rehearsal mechanism may be limited to the relevant blocks, regardless of the total number of blocks on the display. To this end, the number of relevant blocks was fixed at 9, also for the displays comprising 16 and 25 blocks. The structure of the display was again a factor in the design.

Method

Subjects and Design. Forty-eight 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 Experiments 1 and 2. Subjects were randomly assigned to the conditions of a 2 (display: matrix versus random) x 3 (number of blocks: 9, 16 and 25) factorial design with repeated measures on the last factor. The order of the conditions was counterbalanced over subjects.

Materials and Procedure. For both display types the boards assumed the same measurements as those in Experiment 2. In the selection of the nine relevant blocks on the 4x4 and the 5x5 matrices the structure of the 3x3 matrix was maintained. The locations of the nine relevant blocks on the two larger matrix displays are shown in Fig. 3. The relevant blocks on the random displays comprised the nine blocks of the traditional version of the Corsi blocks task. The procedure was the same as in Experiments 1 and 2, except that 4 trials per sequence length were presented. To conceal the purpose of the experiment one filler trial was randomly added at each sequence length. On the displays with 16 or 25 blocks the filler trial consisted entirely, or at least partly, of blocks other than the 9 designated ones. Performance on the filler trials was not included in the assessment of memory span.

Insert Fig. 3 about here

Results

The average recall scores were entered into a multivariate analysis comprising one between-subject factor (structure of the display) and one repeated measure (number of blocks). Hypotheses were tested by means of contrasts in the independent and dependent variables. Mean data for each condition are shown in Table 2.

Insert Table 2 about here

Results yielded main effects of number of blocks [$F(2,45) = 9.80$, $P < 0.001$] and structure [$F(1,46) = 19.27$, $P < 0.001$], but no interaction between these two factors [$F(2,45) = 1.86$, $P > 0.15$]. Separate analyses of variance of the two display types revealed rather different patterns of results for the matrix and the random display conditions. Although span scores on the matrix displays decreased slightly with an increasing number of blocks, there was no significant effect of number of blocks [$F(2,22) = 2.45$, $P > 0.10$]. Furthermore, none of the pair-wise comparisons among the three conditions were statistically reliable. The data of the random displays, however, revealed a clear effect of number of blocks, [$F(2,22) = 6.96$, $P < 0.01$]. Performance systematically dropped with a larger number of blocks in the display. Planned comparisons showed that span scores were reliably higher on a display with 9 blocks than when the display contained 16 [$F(1,23) = 5.86$, $P < 0.05$] or 25 blocks [$F(1,23) = 14.83$, *P* < 0.001]. The difference in results of the two larger displays failed to reach significance [$F(1,23) = 2.72$, $P > 0.10$].

Discussion

The results strengthen the finding of Experiment 1 and 2 that immediate visuo-spatial recall is susceptible to the structural complexity of to-be-remembered information. Memory performance was consistently better in the matrix condition than in the random condition, regardless of the number of blocks on the board.

On the matrix display a similar level of performance was maintained regardless of the number of blocks on the display. Recall scores for the random display, however, decreased with an increasing number of blocks on the board. Results of this condition are consistent with those obtained in the random display in Experiment 2. It seems as if subjects in the matrix condition were conscious of the objective of the experiment. However, when questioned about it after the experiment, subjects in both the matrix and the random display condition claimed not to have been aware of the fact that only 9 blocks had been used on the displays with 16 and 25 blocks. Subjects in the matrix condition apparently gained this knowledge through a process of implicit learning.

Several studies have shown that information can be learned in an incidental manner without awareness of what has been learned (Seger, 1994). For instance, subjects can learn sequences of stimuli that follow a regular pattern, such as letter strings produced by an artificial grammar (Reber, 1989) or spatial orientations (Mayr, 1996), even though they are unaware of the underlying structure.

In the matrix condition subjects learned that only a subset of blocks was used on successive trials without conscious knowledge of this recurrent pattern. Although they were unable to report it, subjects did profit from this implicit knowledge. In the random display condition, however, subjects were unable to detect the existence of the underlying rule applied across the presented sequences. There are indications in the literature that subjects show a bias toward learning particular forms of information, such as patterns with a high level of systematicity or redundancy (e.g. Billman, 1989), and spatially or temporally organised information (e.g. Cleeremans & McClelland, 1991). Likewise, in the present study implicit learning was facilitated by the structure manifest in the display. This is consistent with the view that the presence of structure plays an important role in immediate visuo-spatial recall.

It was argued that the effect of number of blocks in Experiment 2 suggested that the rehearsal mechanism was not limited to the targeted positions. This experiment showed that even when the rehearsal process is focused on a subset of blocks, the total number of blocks on the display still comes into play, unless the blocks are positioned in a structured fashion. The latter clearly demonstrates an interaction between structural and quantitative complexity with respect to visuo-spatial short-term retention.

EXPERIMENT 4

Experiment 4 further explored the effect of implicit learning on visuo-spatial memory span. Quantitative complexity was again manipulated by increasing the number of blocks used, albeit differently from the previous experiments. In each case a display comprising 25 blocks was employed. The displays varied in terms of the number of relevant blocks: 9, 16 or 25. In line with the data obtained in Experiment 2 it was hypothesised that visuo-spatial span would be inversely related to the number of relevant blocks among which the targets had to be discriminated. However, since implicit acquisition of a subset of blocks occurred solely in the matrix condition of Experiment 3, this effect was expected only for the matrix display.

Method

Subjects and Design. Subjects were 66 first-year students enrolled at the Faculty of Psychology and Educational Sciences of the University of Ghent, none of whom had participated in any of the previous experiments. The experiment was a 2 (display: matrix versus random) x 3 (number of relevant blocks: 9, 16 and 25) design. All subjects completed the task on the two display types. With regard to the factor “number of relevant blocks on the display”, subjects were randomly allocated to each condition. Half the subjects performed the task on the matrix display first and then on the random display; for the other half the order was reversed.

Materials and Procedure. The boards of both display types again assumed the same measurements as those in Experiment 2. In the conditions with 9 and 16 relevant blocks on the matrix display the matrix structure was retained. The locations of the 9 relevant blocks were the same as in Experiment 3. The positions of the 16 relevant blocks on the matrix display are shown in Fig. 4. The relevant blocks on the random display assumed their original positions as used in Experiment 2. The procedure was as for Experiment 3.

Insert Fig. 4 about here

Results

Mean span scores were entered into a multivariate analysis with the number of relevant blocks as between-subject factor. The span measures obtained in the two display type conditions were the dependent variables in this analysis. Hypotheses were tested by means of contrasts in the independent and dependent variables. Mean data for each condition are shown in Table 3.

Insert Table 3 about here

The analysis yielded main effects of number of relevant blocks [$F(2,63) = 4.53$, $P < 0.05$] and structure [$F(1,63) = 21.79$, $P < 0.001$]. There was also a significant number of relevant blocks by structure interaction [$F(2,63) = 12.06$, $P < 0.001$]. Planned comparisons revealed an effect of number of relevant blocks for the matrix display [$F(2,63) = 11.75$, $P < 0.001$], but not for the random display ($F < 1$). In the matrix condition all pair-wise contrasts among the three levels of the factor “number of relevant blocks” were significant ($P < 0.05$).

Separate analyses for each of the “number of relevant blocks” conditions yielded higher recall scores in the matrix condition than in the random display condition when the number of relevant blocks was limited to 9 [$F(1,21) = 44.05$, $P < 0.001$], or 16 [$F(1,21) = 8.77$, $P < 0.01$], but not when all 25 blocks on the display were used ($F < 1$).

Discussion

The results of this experiment provide additional support for the view that structural complexity is a salient feature of visuo-spatial short-term retention. Performance was again found to be better on the matrix display than on the random display, except for the condition in which all 25 blocks were taken into account. These findings confirm the effects obtained in Experiment 2.

Furthermore, span scores declined with an increasing number of relevant blocks, but only in the matrix condition. Performance on the random display remained stable regardless of the number of relevant blocks. It can be inferred from these results that performance in the matrix condition may again have benefited from implicit learning. On the displays with 9 or 16 relevant blocks, subjects seemingly picked up on this latent rule. This implicit knowledge was apparently not available on the respective displays in the random display condition. This pattern of results strengthens the idea that structure is an important factor in the implicit acquisition of visuo-spatial information.

The alternative measure of quantitative complexity used in this experiment proved to be equally effective in that it produced results consistent with the previous experiments. Moreover, identical conditions across the various experiments produced similar results. First, the condition with 25 blocks in Experiment 2 is the same as the condition with 25 relevant blocks in Experiment 4, and revealed similar recall scores (see Tables 1 and 3). Second, the condition with 9 relevant blocks out of 25 was included in both Experiments 3 and 4, and also produced similar levels of performance (see Tables 2 and 3).

GENERAL DISCUSSION

The experiments reported here have provided some further insight into the characteristics of the visuo-spatial temporary storage system. First, in all four experiments structure was shown to have a facilitating effect on short-term visuo-spatial retention. Span performance was superior when the blocks constituted a matrix to a display in which the blocks were positioned randomly. A structured display would appear to facilitate the reconstruction of the to-be-remembered path. This greater facilitation may in part reflect the use of long-term knowledge. Studies on spatial suppression effects provide support for this view. Spatial suppression impairs visuo-spatial memory span, but does not completely remove the ability to recall a series of visuo-spatial items (e.g. Smyth et al., 1988). Suppression usually reduces span from about six or seven items to four or five items. Thus, even when the mechanisms for visuo-spatial coding have been eliminated, a residual contribution to memory remains. This contribution may be attributed to long-term memory processes. In the verbal domain the limits of memory span have been shown to reflect the contribution of two underlying mechanisms: the phonological loop and long-term memory (e.g. Hulme, Maughan, & Brown, 1991). Likewise, visuo-spatial memory span may also reflect the operation of both short- and long-term memory components, i.e. the VSSP and long-term memory. Moreover, the contribution from long-term memory to verbal memory span is greater for words than for non-words. Similarly, the finding that visuo-spatial memory span is higher for blocks positioned in a matrix than randomly may be due to fewer long-term memory representations for unstructured material. Further empirical evidence bearing upon this issue is of course required.

Second, quantitative complexity in terms of the number of blocks in the display was found to have an effect on visuo-spatial span. In Experiment 2 subjects did not abstract from the number of blocks on the board: span scores decreased as the number of blocks increased. This finding may be related to the discriminability or confusability of the to-be-remembered items: unlike verbal material, a spatial item has no other identity than its position in relation to the other items in the display. As the number of blocks increases the targeted positions become more difficult to discriminate, giving rise to errors at recall.

This issue was addressed by Smyth and Scholey (1994a). The authors compared visuo-spatial span on a display with 9 blocks with performance on a display with 27 blocks arranged in 9 groups of 3. In the latter only one block from a group of three was presented in any trial. Span scores were poorer with 27 blocks than with 9 blocks. When recall was scored over the nine groups, performance was still considerably lower than on the display with only nine blocks. The authors inferred from these results that encoding and rehearsal of confusable items reduces span. On the nine-block display it is not necessary to encode the exact position of the target to refresh that position, because quite often there are no other blocks in close competition with a particular target. It is sufficient to rehearse the approximate position of the target to support recall. When recall is from nine sets of three blocks an approximate rehearsal strategy is no longer effective. The exact position of the target must be encoded and kept distinct from the other two blocks in the set. Maintenance of the exact target involves a more precise rehearsal process.

This line of reasoning could also be applied to the present study. On the nine-block display each block has a clearly distinct position on the board. Therefore it is sufficient to encode and rehearse the approximate positions of the targets to procure correct recall. An increasing number of blocks, however, reduces the salience of each individual block. As a result subjects have to encode the positions of the targets more precisely and distinguish them from other blocks in their immediate surrounding. In this situation recall requires a more accurate rehearsal strategy. Concomitant with the reduced salience, a larger number of blocks could also induce an increase in the positional uncertainty of the targets. With more blocks on the board subjects may be less certain of their response. Alternatively, performance may be more prone to guessing as the number of blocks increases. Further investigation will tell which of these interpretations is to be preferred.

Experiment 3 was designed to test the hypothesis that subjects would abstract from the total number of blocks in the display, if only a limited number were relevant. This was true for the matrix condition, but not for the random display condition. Moreover, subjects were not aware of this manipulation, implicating a process of implicit learning in the matrix condition. These results demonstrate that the presence of structure facilitates both explicit and implicit learning of visuo-spatial information. The data reported in Experiment 4 support and extend these findings.

From the results of these experiments it is clear that the cognitive component responsible for retaining visuo-spatial material is limited by both structural and quantitative complexity. It was shown that structure, or rather the lack thereof, and the number of items may individually limit the operation of the visuo-spatial system. The data also provide evidence in support of an interaction between these two factors. For example, in Experiment 2 the effect of structural complexity decreased as the effect of quantitative complexity increased. The discrepancy in span on the matrix and the random display diminished and eventually disappeared with an increasing number of blocks. Moreover, in Experiment 3 and 4 performance on the matrix display was consistent with the number of relevant blocks, whereas recall in the random display was subjected to the total number of blocks on the board.

In short, complexity appears to be an important factor in immediate visuo-spatial recall. Visuo-spatial material that is complex in terms of structure or quantity is recalled less well as opposed to information that is simple, similarly to the finding that verbal memory span is poorer for sequences of long words than for sequences of short words. In this respect the effect of complexity may be regarded as an analogy to the word length effect in visuo-spatial working memory.

Despite this obvious similarity, the two effects differ in a number of respects. First, the word length effect pertains to only one dimension, whereas the effect of complexity is multidimensional. Word length comprises solely a quantitative factor, i.e. the amount of speech-based material that can be recalled within a fixed time interval. Complexity, however, constitutes both a quantitative and a structural factor. Second, the word length effect is related to temporal features of stimuli. The verbal system is expressed in units of time, whereas the capacity of visuo-spatial short-term memory is still unclearly defined (Smyth & Scholey, 1992, 1994a). Third, the word length effect is dependent on the operation of the articulatory rehearsal process. Long words (because of the time they take to say) take longer to be reactivated by the process of subvocal rehearsal than short ones. Therefore, more short words can be held in the limited-capacity phonological store than long ones. Likewise, the representation of a complex stimulus also takes up more capacity than that of a simple one. However, it is as yet unclear whether the effect of complexity bears upon the rehearsal process of the VSSP, or whether it loads the storage system, or perhaps both. Alternatively, the two components of complexity may involve different processing mechanisms of the visuo-spatial slave system. The experiments reported here cannot yet give a decisive answer about these alternatives. Further research will be needed to tease apart these possibilities.

There are some indications in the literature for a rehearsal process underlying the maintenance of visuo-spatial material. For example, Watkins, Peynircioglu, and Brems (1984) have provided evidence for a pictorial rehearsal mechanism. Moreover, contemporary dual task studies have shown that encoding and maintenance of a spatial sequence is interfered with by a variety of spatial and movement suppression tasks, such as eye movements (Idzikowski, Dimbleby, Park, & Baddeley, cited in Baddeley, 1986), arm movements (Quinn & Ralston, 1986), sequential spatial tapping (e.g. Smyth et al., 1988), and shifts of spatial attention (Smyth, 1996; Smyth & Scholey, 1994b), analogous to the adverse effect of articulatory suppression on verbal span. However, thus far, no specific response-based rehearsal process has been found in visuo-spatial working memory (Smyth & Scholey, 1992, 1994a), by analogy with the time-based process of articulatory rehearsal.

In conclusion, it is not the intention to make the VSSP a carbon copy of the PL. The assumption of an analogy between the PL and the VSSP is merely a methodological approach to the further exploration of the visuo-spatial slave system. A similar research strategy that led to the theoretical advancement of the PL, may provide further insight into the characteristics of the VSSP. This proved to be a fruitful methodology in the present study. Complexity was shown to be a basic property of temporary visuo-spatial retention. Further investigation of the mechanisms underlying this phenomenon may enhance our understanding of visuo-spatial working memory, analogous to the contribution of the word length effect to the development of the PL.

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FOOTNOTES

1. In all four experiments a repeated measures design was used. Due to the problems with a standard analysis of variance for repeated measurement (for an overview, see McCall & Appelbaum, 1973), a multivariate analysis was performed in each experiment. The hypotheses were tested by means of contrasts in the independent and dependent variables. This is based on suggestions formulated by McCall and Appelbaum (1973) for a correct statistical analysis of repeated-measures designs.

TABLE 1

Average Span Scores as a Function of Display and Number of Blocks in Experiment 2 (Standard Deviations in Brackets)

	Number of Blocks		
Display	*9*	*16*	*25*
Matrix	6.39 (0.61)	5.79 (0.88)	4.84 (1.19)
Random	5.62 (0.71)	5.15 (0.78)	4.79 (0.76)

TABLE 2

Average Span Scores as a Function of Display and Number of Blocks in Experiment 3

(Standard Deviations in Brackets)

	Number of Blocks		
Display	*9*	*16*	*25*
Matrix	6.32 (0.76)	6.29 (0.85)	5.97 (0.80)
Random	5.70 (0.73)	5.16 (0.89)	4.83 (0.71)

TABLE 3

Average Span Scores as a Function of Display and Number of Relevant Blocks in Experiment 4 (Standard Deviations in Brackets)

	Number of Relevant Blocks		
Display	*9*	*16*	*25*
Matrix	5.97 (0.90)	5.38 (0.46)	4.80 (0.90)
Random	5.06 (0.77)	4.89 (0.97)	4.95 (0.49)

FIGURE CAPTIONS

1. The three displays used in Experiment 1: a regular matrix, a semi-structured display and a random array.
2. The two larger random displays used in Experiment 2.
3. The two larger displays of the matrix condition used in Experiment 3. The relevant blocks are in black.
4. The positions of the 16 relevant blocks on the matrix display used in Experiment 4.

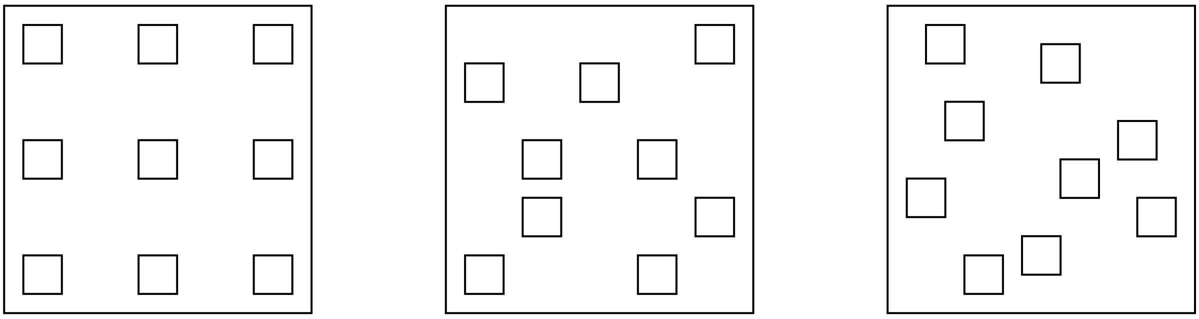

FIG. 1.

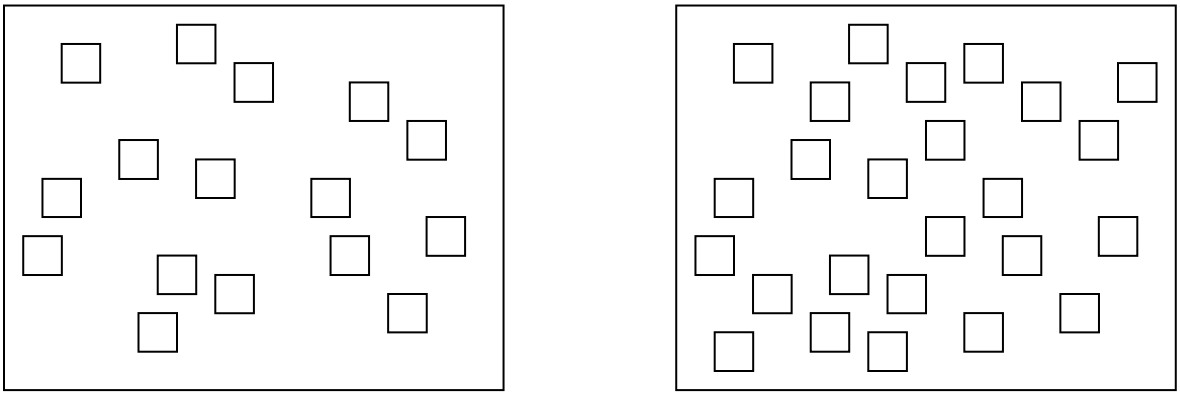

FIG. 2.

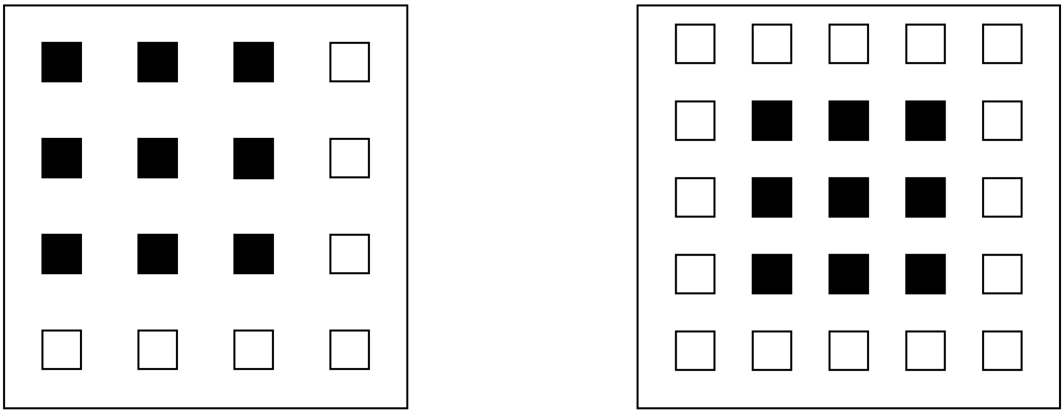

FIG. 3.

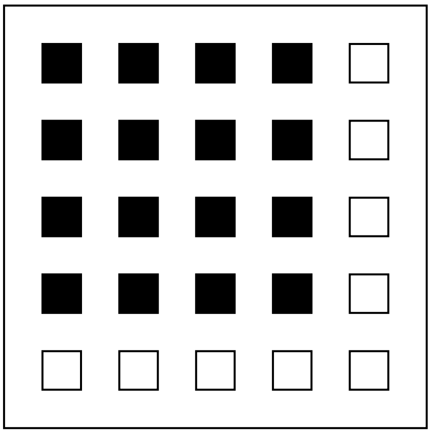

FIG. 4.