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Imposing structure on a Corsi-type task: Evidence for hierarchical organisation based on spatial proximity in serial-spatial memory

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Abstract

Structure was imposed on a tapping task by requiring participants to reproduce sequences of responses to icons organised in spatial clusters. A first experiment featured sequences either segregated or not segregated by clusters. Accuracy was higher for sequences segregated by clusters. Moreover, inter-response times were longer at cluster boundaries than within cluster boundaries. To rule out possible confounding effects of movement length, this temporal pattern was replicated in a second experiment requiring a single response indicating the next sequential step, following the presentation of a portion of a previously practised sequence. These results suggest that sequence reproduction can be sustained by a hierarchical representation based on spatial proximity and provide a first indication of the role of spatial structure in serial-spatial memory.
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1. Introduction

We are constantly faced with the problem of having to temporarily retain serial-spatial information in order to keep track of sequences of displacements of objects and to plan and execute sequences of movements in space.

The Corsi Tapping Test (CTT), or basic variations of it, is one of the most popular experimental tools for the assessment of serial-spatial temporary memory and the factors that influence it. Initially developed by Corsi (1972) for his unpublished dissertation, and presented to a wider scientific readership by Milner (1971), the CTT, as originally devised, required the participants to reproduce a sequence of tapping responses previously performed by the tester on an array of wooden blocks.

In recent years, the Corsi test has been used in a growing body of research on serial-spatial memory that has been accumulated following the development of the working memory model (Baddeley & Hitch, 1974).

Within this framework, independent sub-systems have been identified that are specifically dedicated to the processing of either verbal (the phonological loop) or spatial information: (the visuo-spatial scratch-pad). In a recent review, Baddeley (2001) indicates the CTT as the test that is most closely associated with spatial short-term memory on the basis of both behavioural and neuropsychological evidence.

Although research on working memory has initially focused mainly on the verbal processing sub-system (as pointed out, for example, by Jones, Farrand, Stuart, & Morris, 1995; Logie, 1995), more recently, research on the visuo-spatial component of the model has enjoyed a renewed interest and major advancements have been made in our understanding of its characteristics and functions. For example, on the basis of careful experimental investigations, a sub-system of the visuo-spatial scratch-pad has been suggested, the "inner scribe," that would be specifically responsible for the retention and processing of spatial information and would play an essential role in processing and planning movement sequences (Logie, 1995; Logie & Marchetti, 1991). The

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CTT seems to capture accurately the working of the inner scribe, as performance on this test seems to rely on a purely serial spatial component of working memory that is selectively affected by the concurrent presentation of spatial but not visual tasks (Logie, 1995; Reisberg & Logie, 1993; Salway & Logie, 1995) and tasks that make demand on spatial attention (Smyth & Scholey, 1994b). Performance on CTT shows, moreover, a double dissociation with visual tasks in neuropsychological patients (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999), and presents developmental fractionation with visual tasks (Logie & Pearson, 1997).

Movement per se has recently received further emphasis through a proposed distinction, within the visuo-spatial scratch-pad, of sub-systems specialised for processing static and dynamic information (Pickering, Gathercole, Hall, & Lloyd, 2001), the latter being conveyed by tasks with a strong serial component. CTT performance seem to rely on resources that are specifically allocated to the processing of movements to spatial targets and independent from the resources used for the processing of configurations of movements, such as hand configurations or body postures (Smyth, Pearson, & Pendleton, 1988; Smyth & Pendleton, 1989, 1990).

Although the CTT has enjoyed an enormous popularity in both experimental research and clinical practice, it is unfortunate, as pointed out by Berch, Krikorian, and Huha (1998) in a recent review, that in different studies featuring the CTT almost every task parameter (ranging from the block arrangement to the scoring method) has been varied, often without providing an adequate description of important procedural details (Berch et al., 1998).

It seems particularly surprising that very little, if any, consideration has been given to the potential importance of the relative spatial position of the blocks and how spatial constraints might interact with the particular sequence to be reproduced. Berch et al. (1998) note that none of the 38 studies included in their review, including the original work by Corsi (1972), had reported the relative distance between the blocks.

When studying serial memory in non-spatial domains it is possible to devise relatively unstructured material, such as lists of non-sense words. By contrast, in the spatial domain structural constraints are always present and might play a role in how the information to be retained is organised in a serial representation. An observer can always detect structure in the spatial layout of the environment, provided, for example, by the relative spatial proximity of different objects or their location along spatial vectors.

An example of constraints that can be used in a spatial display is provided in Fig. 1A, which depicts a typical arrangement of blocks featured in a Corsi-type task. Even in this relatively unstructured configuration, it is possible to see how some blocks (e.g., blocks B and D
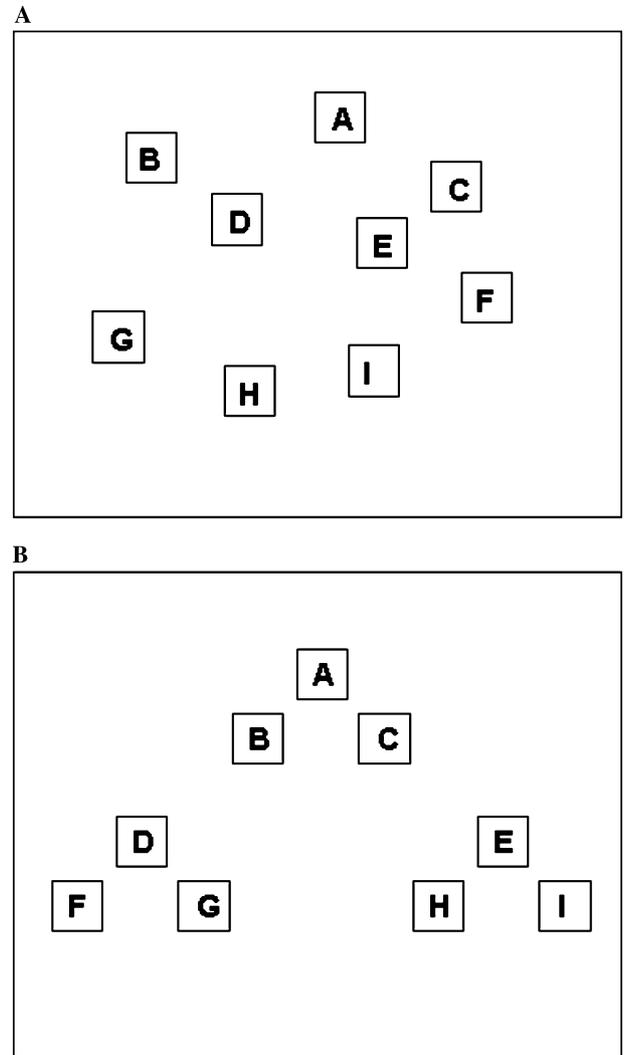

Fig. 1. An example of a conventional configuration of items used in Corsi-type tasks (A) and of a clustered configuration as featured in the present study (B).

and blocks C and E) can be perceptually grouped on the basis of their spatial proximity and that the array can be segmented in three diagonal lines (i.e., blocks A–C; B–D–E–F; and G–H–I).

In those studies which have reported a graphical depiction of the block arrangement, it is possible to detect variations in the way in which the blocks form sub-groupings and clusters based on spatial proximity (see Berch et al., 1998, Fig. 2). Even when the spatial configuration was kept constant, it has been shown that the use of different tapping paths through the block-array selectively affects the ability of the participants to reproduce sequences of the same number of ordinal steps (Smirni, Villardita, & Zappala', 1983).

However, the question of why some sequences should be easier to reproduce than others has not been specifically addressed. The fact that participants might find some sequences easier to remember has been mostly

used as an argument highlighting the need for standardisation of the Corsi test for experimental and clinical testing (Kessels, Zandvoort, Postma, Kappelle, & Haan, 2000; Smirni et al., 1983). One possible explanation of the difference in performance according to the particular sequence presented is that even in the relatively unstructured configuration normally used in Corsi-type tasks, the serial structure of some sequences might collude with the spatial arrangement of the display to make it possible to use spatial structure as a memory offloading device. For example, a long sequence might be hierarchically encoded by segmenting it into sub-sequences defined by spatial clusters or linear structures.

It is, however, difficult to identify a posteriori what type of spatial constraints people might spontaneously use in order to reproduce given sequences in displays such as that depicted in Fig. 1A. It is, therefore, necessary to test specific hypotheses concerning the type of spatial constraint used to aid memory performance for given sequences by using configurations that explicitly afford a particular type of organisation and compare performance on sequences that are consistent with that particular type of organisation with sequences that are not. For example, the clustered display presented in Fig. 1B affords the segregation of a 9-item sequence into three 3-item sub-sequences defined by each spatial cluster. Thus, performance on a sequence such as ABC DFG EHI that is segregated by spatial clusters can be compared with performance on a sequence such as AHB DEC FEG that is not, in order to assess whether this type of constraint facilitates performance or not.

Some attention to the effects of different displays on spatial span in a Corsi-type task has been given by Smyth and Scholey (1994a). In an attempt to find an analogy to the articulatory loop in spatial memory, this study featured a set of experiments aimed at assessing the effect of movement time (time required to point to icons located at different distances on the screen and presumably related to the time required to rehearse their serial locations, in analogy to the word length effect observed in verbal working memory) on subjects' performance. The first two experiments presented in the study failed to support the hypothesis that an increase in the length of movements had an effect on spatial memory span. However, the study featured a third experiment where icons were organised into clusters and participants were required to reproduce sequences featuring only one of the icons within each cluster. The rationale for grouping the icons in spatial clusters was to ensure that subjects were taking into account the precise location of the target (in order to distinguish it from other items in spatial proximity) when rehearsing the sequence. In this last experiment a negative relationship between the distance between the items in the sequence and memory span was observed and this result was used

to support the claim that rehearsal time affects spatial span, similarly to what has been reported for serial verbal memory (Baddeley, Thomson, & Buchanan, 1975).

In the study of Smyth and Scholey (1994a) it was observed that generally memory span for items presented within an array featuring spatial clusters is impaired compared to sequences of similar length but presented within an array where icons are not organised into clusters. This result is interpreted by the Authors in terms of an increase in the confusability of icons presented in spatial proximity. However, as mentioned above and in line with the rationale of their study, in the Smyth and Scholey's study (1994a) participants were not faced with sequences where all the items within a cluster had to be selected before moving onto another sub-set of icons grouped on the basis of spatial proximity.

Although very informative in highlighting analogies and differences in the rehearsal mechanisms underlying spatial and verbal working memory and although in one of their experiments icon displays featuring explicit spatial structure were used, the study by Smyth and Scholey (1994a) did not address the issue of whether spatial clustering in a Corsi-type task can support the emergence of hierarchically organised representations of the sequence which, in analogy with psychological chunking in other domains, can help the reduction of the memory load imposed by the task.

Hierarchical models of sequence reproduction in the verbal domain, have been supported by time analyses in studies requiring the participants to repeat, by speaking or typewriting sequences of words or grouped strings of letters presented on a computer monitor (Sternberg, Knoll, Monsell, & Wright, 1988; Sternberg, Knoll, & Turock, 1990). Nevertheless, due perhaps to the lack of interest in the role played by spatial constraints in the way material is organised in short-term memory or the failure to recognise its importance, very little seems to be known to date about the forms of representation that might underpin the efficient reproduction of serial responses to material featuring an explicit spatial structure.

The aim of the present study is to begin to address this issue by using a task similar to the CTT. However, in contrast with previous studies based on the CTT, here an explicit form of spatial organisation, based on spatial clustering was presented, and the serial structure of the sequence was manipulated so that some sequences were segregated by clusters and some were not.

The use of computerized procedures for the administration of Corsi-type tasks is becoming increasingly widespread and it is recommended rather than the use of the more traditional version featuring wooden blocks (Berch et al., 1998).

The obvious differences between computerised versions and traditional versions of the task (such as the use

of two-dimensional as opposed to three-dimensional stimuli, the vertical instead of horizontal presentation of the stimulus array and the fact that changes in brightness or colour of the stimuli indicate the path sequence instead of the manual pointing of the tester) do not seem to play a significant role in the relevant response variables (Fischer, 2000). Furthermore, computerised versions of the task, especially if implemented using touch-sensitive computer monitors, offer, among others (see Berch et al., 1998; for a more extensive list) the advantage of enabling the recording of response latencies. Indeed a time analysis of the response of the participants has recently proved to be an indicator of important aspects of the way in which sequences of responses are planned and represented in Corsi-type tasks (Fischer, 2000).

By featuring an analysis of the pattern of RT shown by participants faced with a sequence reproduction task within an array of spatially clustered icons, the present study aimed to identify basic forms of organisation within serial-spatial memory.

2. Experiment 1

The aim of Experiment 1 was to assess whether sequences that are segregated by spatial clusters are reproduced more accurately than sequences that are not segregated by spatial clusters. Moreover, in order to test the hypothesis that a hierarchical representation underpinned the reproduction of sequences segregated by clusters, RT were analysed to ascertain whether longer latencies were observed for responses located at cluster boundaries.

The emergence of peaks of RT at critical points during the execution of serial responses has been considered evidence for a hierarchical representation of a learned sequence in paradigms requiring the reproduction of verbal material by speaking or typewriting (Sternberg et al., 1988; Sternberg et al., 1990), in the retrieval of letters from a memorized alphabet (Klahr, Chase, & Lovelace, 1983), in the serial learning of responses to icons presented on a computer monitor (Terrace, 2001), and in computational models of human learning (Gobet et al., 2001).

The interpretation of these patterns of RT varies according to the paradigms and the theoretical framework used in different studies. Sternberg et al. (1988, 1990) proposed a hierarchical model whereby longer latencies at the beginning of the production of sequences of words and pauses at the transition between words were considered an expression of the planning of the sequence in terms of the ordinal position of the words and the time taken to retrieve the sub-routines responsible for the ordering of syllables within the words, respectively.

More often models have been proposed where the hierarchical coding of serial information is based on chunking. The concept of psychological chunking has been used broadly to characterise hierarchical coding based on the relative associative strength of links between elements of a sequence (Cowan, 2000; Gobet et al., 2001). Other Authors refer to chunking to indicate more sophisticated forms of semantic categorisation in list learning (Bousfield & Bousfield, 1966; Bower & Winzenz, 1969). Despite differences in how the process of chunking is defined, different models converge in predicting longer RT at chunking boundaries and a facilitatory effect of chunking in the retention of serial information (Bousfield & Bousfield, 1966; Bower & Winzenz, 1969; Gobet et al., 2001; Terrace, 1987; Terrace, 1991).

Thus the rationale of the present experiment was based on the prediction that if people, when given the opportunity to do so, spontaneously form hierarchical representations based on spatial clustering in a Corsi-type task, sequences that are compatible with such principle should be easier to reproduce. Moreover, during the execution of sequences compatible with a hierarchical organisation based on spatial clustering longer RT at cluster boundaries should be expected.

2.1. Materials and methods

2.1.1. Participants

Twenty undergraduate students, 16 females and 4 males aged between 18 and 21 (mean = 19) took part in this experiment as part of their course requirements. All the participants had normal or corrected to normal vision and were not aware of the hypotheses of the experiment.

2.1.2. Apparatus

A Pentium PC 233 MMX equipped with a 17 in. Micro Touch, True Point touch-sensitive monitor. Software developed in-house allowed the presentation of a visual display consisting in 9 identical grey squares (side 2.5 cm) arranged in three spatial clusters of three icons each (see Fig. 2). The minimal distance between icons within the same cluster was of 0.5 cm and the maximum of 4 cm, whereas the minimal distance between icons belonging to different clusters was of 6 cm and the maximum of 16 cm. The icons blinked (disappeared for 0.5 s) according to particular sequences, which the participants had to reproduce by touching the icons on the screen. The serial order of the touches and their latencies were recorded.

2.1.3. Procedure

Participants were tested individually in a quiet room. They were asked to sit comfortably in front of the computer at a distance (roughly one arm's length from the screen) that allowed them to reach any point on the
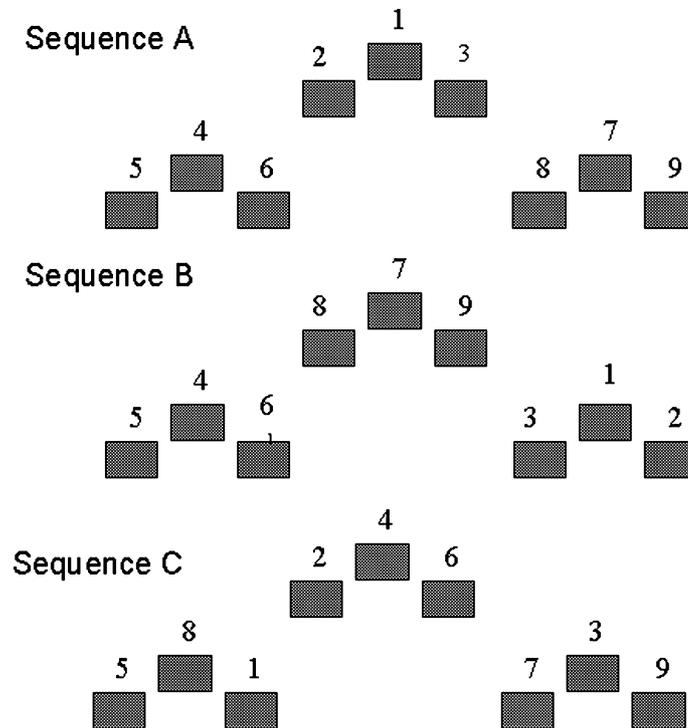
Fig. 2. Configurations and sequences presented in Experiment 1. Sequence A (top), Sequence B (middle), and Sequence C (bottom). Numbers indicate the order of the required pointing response. Size of the icons and relative distances are not to scale.

monitor with the their index finger. A configuration of icons, identical to the configuration used through the experiment (see Fig. 2), was then presented on the monitor and the participant was asked to touch all the icons in any order. This was done in order to ensure that the participant could easily reach all the icons on the screen and that the computer was registering the touches. The experiment proper ensued. The participants were informed that the visual display would have reappeared, at the beginning of each experimental trial, and that, as they watched, the icons would blink according to particular sequences. They were asked to remember the order in which the icons blinked. They were told that a countdown of 4 s would be displayed and that they had to reproduce the observed sequence by touching the icons in the appropriate order using their index finger.

2.1.4. Design

Each participant received a daily testing session consisting of 18 trials, divided according to the following sequence type:

Sequence A. The sequence was segregated by clusters and the same movement pattern was repeated within each cluster (see Fig. 2, top).

Sequence B. The sequence was segregated by clusters but different movement patterns were presented for different clusters (see Fig. 2, middle).

Sequence C. The sequence was not segregated by clusters and, therefore, not compatible with a hierar-

chical representation based on spatial proximity (see Fig 2, bottom).

Six sequences of each type were interspersed in a daily testing session, according to a pseudo-random order of presentation that prevented two sequence of the same type to be presented in successive trials.

2.2. Results and discussion

2.2.1. Reproduction accuracy

The mean number of Sequences, A, B, and C, correctly reproduced by the participants, is presented in Fig. 3.

A one-way repeated measures ANOVA on the frequency of correct sequence reproduction observed for Sequences A, B, and C showed a significant main effect for Sequence type [$F(2, 38) = 42.789, p < .001$]. Pairwise comparisons showed that the frequency of correct sequence reproduction observed for Sequence A was significantly higher than for Sequence B [$t(19) = 3.356, p < .01$] and for Sequence C [$t(19) = 10.262, p < .001$]. The frequency of correct sequence reproduction for Sequence B was in turn significantly higher than that observed for Sequence C [$t(19) = 5.748, p < .001$].

Therefore, participants found the reproduction of sequences compatible with a hierarchical representation based on spatial proximity less demanding than sequences not affording this form of organisation. Moreover, within sequences compatible with a hierarchical
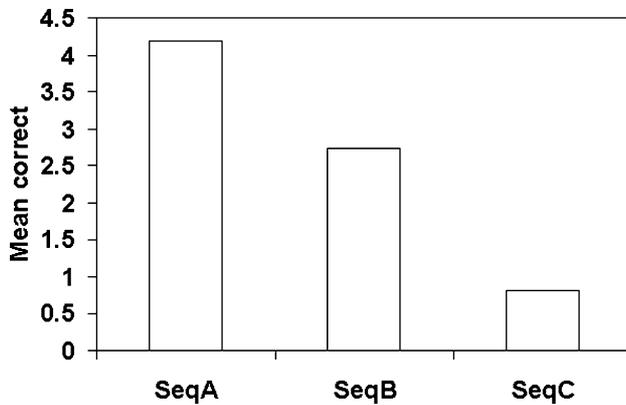
Fig. 3. Average frequency of Sequences A, B, and C correctly reproduced in Experiment 1.

organisation based on spatial proximity, the participants found it easier to reproduce sequences where the same movement pattern was re-proposed for different clusters.

2.2.2. Time analysis

In order to evaluate whether the observed increase in accuracy for sequences compatible with a hierarchical representation based on spatial proximity was supported by such a form of representation a time analysis was carried out. Its aim was to assess whether, for the sequences compatible with a hierarchical representation, touch latencies increased at cluster boundaries. Only correctly reproduced sequences were included in the analysis (see Fig. 3 for mean frequencies of correct sequence reproduction). Fig. 4 shows the mean reaction times plotted against the serial order of the touches. In the figures and throughout the text, touches corresponding to the different ordinal positions within the sequences will be referred to as T1 (first step in the sequence), T2 (second step in the sequence),...,Tn (nth step in the sequence).

As can be observed from the figure, for Sequences A and B the response initiation time (T1) and RT corresponding to inter-cluster transitions (T4 and T7) are considerably longer than the latencies for intra-cluster transitions. This pattern of results was confirmed by one-way repeated measures ANOVAs and pairwise comparisons carried out on the mean latencies observed for responses at different ordinal steps in each of the two sequence, as described below.

Sequence A. A significant main effect $[F(8, 152) = 28.818, p < .001]$ was observed for the serial order of touches in this condition. Planned comparisons carried out using t tests revealed that the initial response time was longer than other pointing responses located within the same cluster boundary [T1 vs. T2 $(t(19) = 5.77, p < .001)$; T1 vs. T3 $(t(19) = 5.97, p < .001)$] and that subsequent responses at cluster boundaries always showed a longer RT than responses within cluster boundaries [T4 vs. T5 $(t(19) = 5.54, p < .001)$; T4 vs. T6 $(t(19) = 4.46,$
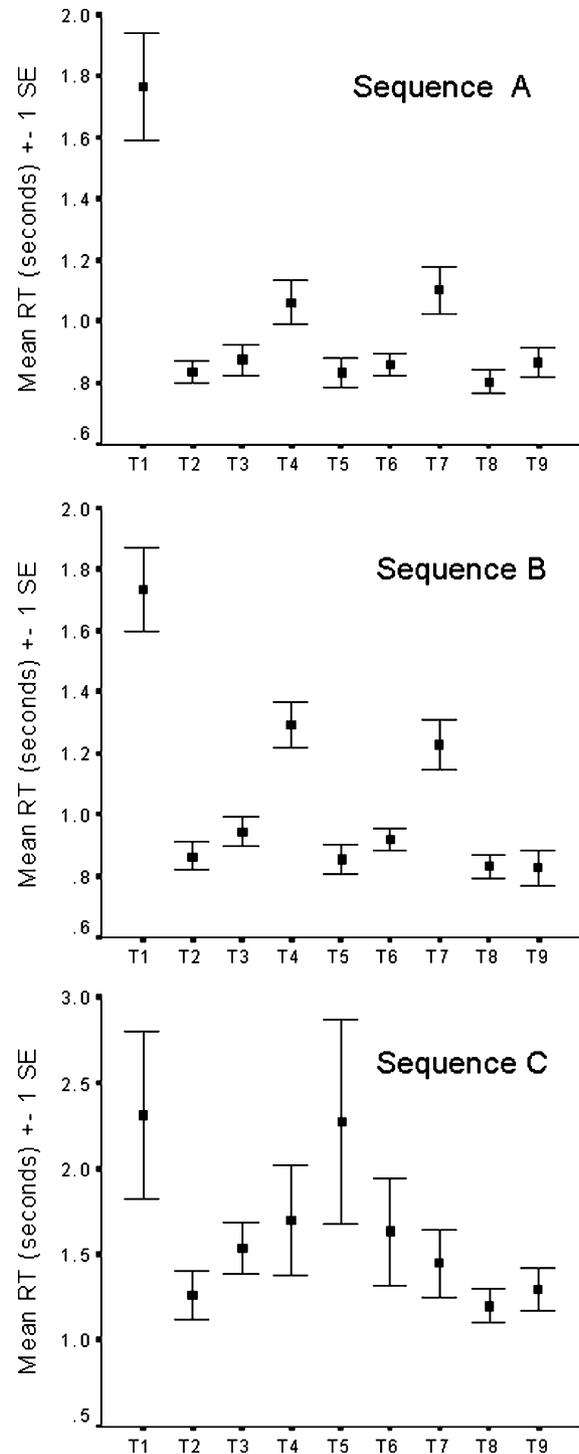

Fig. 4. Mean RT and standard error observed in Experiment 1 for responses corresponding to different ordinal steps (T1–T9) in the reproduction of Sequences A (top), B (middle), and C (bottom). In sequences A and B, T4 and T7 correspond to responses at cluster boundaries.

$p < .001$); T7 vs. T8 $(t(19) = 5.32, p < .001)$; T7 vs. T9 $(t(19) = 4.41, p = .001)]$.

Moreover, the response initiation time, T1, proved longer than response times at cluster boundaries, T4

$[t(19) = 4.73, p < .001]$ and T7 $[t(19) = 4.27, p < .001]$ whereas the comparison of the RT for T4 and T7 was not significant.

Overall, when the averaged RT for responses at cluster boundaries (T4 and T7) was compared with the average RT for responses within cluster boundaries, the former proved longer than the latter $[t(19) = 5.72, p < .001]$.

Sequence B. As for Sequence type A, a significant main effect $[F(8, 144) = 32.970, p < .001]$ was observed for responses corresponding to different ordinal steps in the sequence. Pairwise comparisons revealed a difference between T1 and subsequent responses within the same cluster [T1 vs. T2 $(t(18) = 7.67, p < .001)$; T1 vs. T3 $(t(18) = 6.37, p < .001)$]. Statistically significant differences emerged also for subsequent responses at cluster boundaries and the corresponding responses within cluster boundaries [T4 vs. T5 $(t(18) = 6.41, p < .001)$; T4 vs. T6 $(t(18) = 5.13, p < .001)$; T7 vs. T8 $(t(18) = 5.42, p < .001)$; T7 vs. T9 $(t(18) = 4.83, p < .001)$].

Moreover, the response initiation time, T1, proved longer than responses at cluster boundaries T4 $[t(18) = 3.86, p = .001]$ and T7 $[t(18) = 3.94, p = .001]$ whereas the comparison of the RT for T4 and T7 was not significant.

Finally, as for Sequence A, a comparison of the average RT for touches at cluster boundaries (T4 and T7) with the average RT for touches performed within cluster boundaries, revealed that mean RT for responses corresponding to cluster boundaries were longer than the mean RT for responses within cluster boundaries $[t(18) = 7.11, p < .001]$.

Thus the pattern of latencies emerging from the time analyses carried out for Sequences A and B is consistent with the prediction that longer latencies should be expected at cluster boundaries if the sequences are represented hierarchically in memory.

By contrast, as can be observed in Fig. 4, a different pattern of latencies emerged for Sequence C that was not compatible with a hierarchical representation based on spatial proximity. The statistical analysis of the pattern of RT observed in Sequence C is reported below.

Sequence C. The one-way repeated measures ANOVA carried out on the latencies observed for each touch in this sequence also showed a significant main effect $[F(8, 56) = 2.49, p < .05]$

This effect however, here seems to be accounted for merely by the longer latencies observed for the response initiation time T1 as the effect disappears when a repeated measures ANOVA is carried out for touches T2–T9, and T1 is excluded from the analysis. Although no statistically significant differences between the RT corresponding to different ordinal points (when T1 is excluded) emerge for Sequence C, it is interesting to note that an ocular inspection of Fig. 4 reveals that the pattern of RT in this sequence starts to resemble a serial

position curve as it would be expected if the sequence is not represented hierarchically, in analogy with list learning of non-structured material in other domains.

Overall the results obtained from Experiment 1 show that subjects found it easier to re-produce sequences segregated by spatial clusters than sequences not segregated by spatial clusters. Among sequences segregated by spatial clusters, the participants found it easier to reproduce sequences where the same pattern of movements was required within each cluster. The time analysis performed on the data provided a first indication of a hierarchical representation of the sequence based on spatial grouping. A longer RT was observed for responses corresponding to ordinal steps of the sequence located at cluster boundaries compared to the RT corresponding to sequence steps located within cluster boundaries, suggesting that at that point of the sequence subjects were exiting the lowest level of a hierarchically organised representation in order to access a node at a higher level of the hierarchy.

It was also observed that the response initiation time was longer than any other RT in the sequence. This is consistent with the results obtained by Sternberg and colleagues (Sternberg et al., 1988, 1990; Wright, 1990) in the context of speech production and typewriting. A hierarchical model such as that proposed by Sternberg and colleagues if applied to the spatial tasks developed here would predict a long response time at the beginning of each sequence. This latency should be expression of the time taken to retrieve the plan for the sequence in terms of the order of interrogation of the different clusters (the higher level of the hierarchy) added to the time taken to retrieve the sub-routine responsible for the exploration of the first cluster. By contrast, the latency to touch the first icon of each of the remaining clusters, once the first cluster has been exhaustively explored, should be shorter since it would only be expression of the time taken to retrieve the sub-routine necessary for the exploration of each particular cluster. Finally, the time taken to touch each of the remaining icons within a cluster should be the shortest since the sub-routine for the exploration of that particular cluster has already been selected.

The results would also be compatible with other hierarchical models based on chunking in other domains (see for example, Gobet et al., 2001; Terrace, 2001) and could potentially indicate that spatial chunks can be formed on the basis of spatial proximity in serial-spatial memory.

However, in Experiment 1, the presence of a confounding variable, namely the time taken to perform movements of a given length, weakens the interpretation of the observed pattern of RT in terms of hierarchical organisation. It is possible that the time taken by the subjects to move their finger on the screen in between-cluster transitions is the sole cause of the observed

pattern of latencies. This kind of explanation could account for the results without having to invoke any underlying hierarchical representation of the sequence.

By requiring a single pointing response indicating the next sequential step in learned sequences, Experiment 2 was specifically designed to assess whether evidence for hierarchical organisation of sequence representation could be obtained in situations where the length of the movements required could not systematically affect the results.

3. Experiment 2

Time to generate the next step in the sequence has been traditionally used to infer the nature of representations and cognitive processes underpinning serial memory in non-spatial domains. For example, Sternberg (1969) investigated the search processes operating upon the representation of serial-order information by requiring subjects to memorise a list of digits before being presented with a probe and asked to generate the next sequential step.

The analysis of time to generate the next step in the sequence has also enabled the detection of forms of hierarchical representation in memory for long strings of items such as the alphabet. The logic here is that peaks in RTs should occur when the probe and the next item (i.e., the letter to be generated in the case of the alphabet) are separated by a sub-group or chunk boundary in the hierarchical representation of the sequence. Experimental and modelling data, for example, confirm that in the case of the representation of the alphabet the longest reaction times are observed when the probe is the last letter of a chunk and the shortest when the probe is the first letter of a chunk (Klahr et al., 1983).

By using a similar technique, adapted for the spatial task at hand, Experiment 2 aimed to clarify the data obtained in Experiment 1. Following a phase in which participants practised the reproduction of a particular sequence, the present experiment, featured a phase where participants were asked to select the icon corresponding to the next step in the sequence when prompted by the presentation of a portion of the sequence. The use of a portion of the sequence, starting from step one, was preferred to the use of a single blinking icon as a probe in order to discourage the participants from engaging in a strategy consisting in searching the entire serial representation from the beginning in every trial until the probe was identified and the next step generated, since this process could have linearly affected RTs as a function of the ordinal position of the probe.

In this second phase it was thus possible to prevent longer movements to be systematically required at cluster boundaries and to assess whether, as predicted

by the notion of a hierarchical representation of the sequence based on spatial proximity, longer latencies would emerge when the last item of the presented portion of the sequence and the icon to be responded to were separated by a cluster boundary, in the absence of the potentially confounding effects of movement length.

3.1. Materials and methods

3.1.1. Participants
Sixteen undergraduate students, 2 males and 14 females, aged between 18 and 26 (mean = 19.5) took part in the experiment as part of their course requirement.

3.1.2. Apparatus
The same as Experiment 1.

3.1.3. Design
The experiment comprised two phases, a training phase and a testing phase. The two phases were presented to each participant in a single testing session, with the testing phase following the training phase. As in Experiment 1, all participants were faced with a configuration of 9 grey squares arranged as three spatial clusters of three icons each. In order to ensure that the results were not affected by the particular sequence used, three different sequences, Sequences A, B, and C were used. All the three sequences were of nine ordinal steps, segregated by spatial clusters, and requiring a different pattern of movement within each cluster (similar to Sequence B of Experiment 1). Each participant was randomly allocated to one of the three sequences. Sequences A and C were presented to five participants and Sequence B to six participants. Configurations and sequences used in Experiment 2 are presented in Fig. 5.

3.1.4. Procedure
Training phase. The procedure used for the training phase closely resembled the procedure adopted in Experiment 1. Each participant was asked to sit comfortably in front of the computer at a distance of one arm's length so that they could reach with the their index finger any point on the monitor. Each trial started with the presentation of the configuration of icons. The icons blinked in the order prescribed by the particular sequence to which the participant had been allocated. The participants were instructed to watch the sequence of blinks carefully and, following a countdown of 4 s, to repeat the sequence back by touching the icons on the screen using their index finger. This phase comprised 10 trials.

Testing phase. The presentation of the testing phase followed the completion of the training phase. Each trial in this phase started with the presentation of the sequence practised during the training phase. Then, following a 1 s interval, the configuration of 9 icons
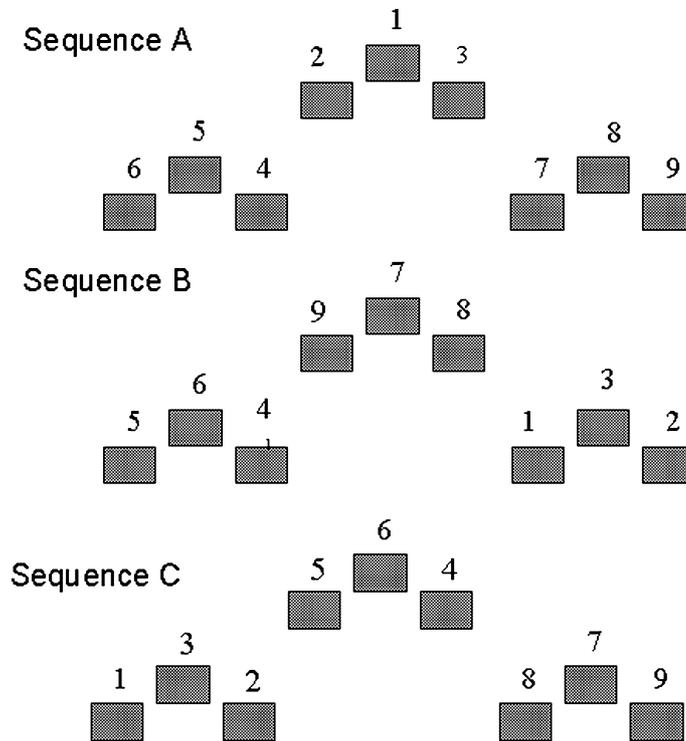
Fig. 5. Configurations and sequences presented in Experiment 2. Sequence A (top), Sequence B (middle), and Sequence C (bottom). Numbers indicate the order of the required pointing response. Size of the icons and relative distances are not in scale.

reappeared and a portion of the original sequence was presented, always starting from the beginning of the sequence. A tone was produced when the last item of the portion of the sequence blinked. The participants were instructed to identify, on hearing the tone, the next ordinal step in the sequence (i.e., the icon that would have blinked if the sequence had not been interrupted) that they had previously observed (and practised during the training phase) by touching the corresponding icon. This phase comprised 80 trials, 10 for each of the eight possible correct responses (T2–T9) at each ordinal step of the sequence, excluding step one. The trials were interspersed in a pseudo-random order preventing two identical trials from appearing consecutively. The experimental software enabled the collection of response locations and RT. The participants were asked to rest their hand on a pad located centrally in front of the computer between trials in order to ensure that each response movement started from a fixed location.

3.2. Results and discussion

Training phase. Mean RT observed for responses at each ordinal step in the sequence are reported in Fig. 6. Only RTs for correct responses were included in the analysis (78.2% of the total number of responses).

A 9 (ordinal step of the response) × 3 (sequence type) mixed ANOVA carried out on the RT corresponding to responses at different ordinal positions in the sequence
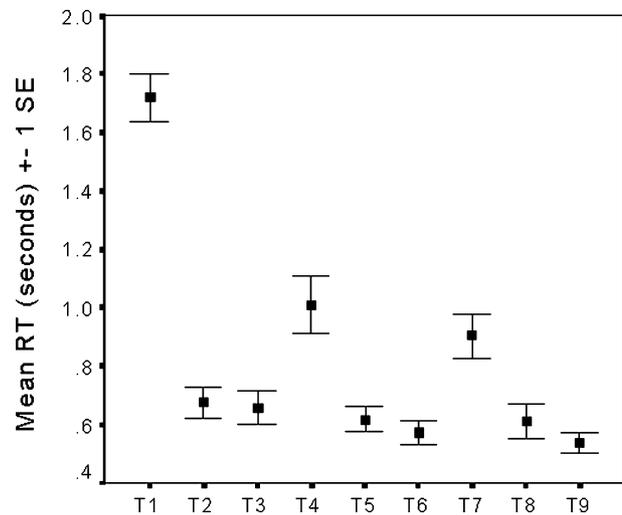

Fig. 6. Mean RT and standard error observed in the training phase (sequence reproduction) of Experiment 2 for responses corresponding to different ordinal steps (T1–T9) in the sequence. Results obtained for Sequences A, B, and C were combined for the analysis. T4 and T7 correspond to responses at cluster boundaries.

revealed a significant main effect for the ordinal step of the response $[F(8, 104) = 58.48, p < .001]$. By contrast, neither the factor sequence type nor the interaction ordinal step of the response by sequence type proved significant. Given the absence of an effect of sequence type and of an interaction between sequence type and ordinal step of the response, the data for the three sequences were combined

in further analyses. Sequence initiation time (T1) proved longer than any pointing response within the same cluster boundary and longer than subsequent responses at cluster boundaries [T1 vs. T2, $t(15) = 12.66$, $p < .001$; T1 vs. T3 $t(15) = 12.81$, $p < .001$; T1 vs. T4, $t(15) = 5.99$, $p < .001$; T1 vs. T7, $t(15) = 7.89$, $p < .001$]. In turn, responses at cluster boundaries (T4 and T7) showed a longer RT than pointing responses within cluster boundaries [T4 vs. T5, $t(15) = 4.13$, $p = .001$; T4 vs. T6, $t(15) = 4.60$, $p < .001$; T7 vs. T8, $t(15) = 6.04$, $p < .001$; T7 vs. T9, $t(15) = 5.79$, $p < .001$]. Overall, when the average RT for touches at cluster boundaries (T4 and T7) and the average RT for touches within cluster boundaries were compared, the former proved longer than the latter [$t(15) = 5.15$, $p < .001$].

Testing phase. Mean RT observed for responses at each ordinal step in the sequence are reported in Fig. 7. Only RT corresponding to correct responses were included in the analysis (96.72% of the total number of responses).

A 8 (responses corresponding to different ordinal steps in the sequence, T2–T9) × 3 (sequence type) mixed ANOVA carried out on the latencies observed for touches corresponding to different ordinal positions in the learned sequence revealed a significant main effect for responses corresponding to different ordinal steps in the sequence [$F(7, 91) = 4.32$, $p < .001$]. By contrast, neither the factor sequence type nor the interaction sequence by responses corresponding to different ordinal steps in the sequence proved significant. As for the training phase, data obtained from the three sequences were therefore combined before performing pairwise comparisons between responses corresponding to different ordinal steps in the sequence.

The two touches, T4 and T7 corresponding to responses at cluster boundaries proved longer than the respective responses corresponding to ordinal steps within cluster boundaries [T4 vs. T5, $t(15) = 2.50$, $p < .05$; T4 vs. T6, $t(15) = 2.95$, $p < .05$; T7 vs. T8, $t(15) = 2.313$, $p < .05$; T8 vs. T9, $t(15) = 2.35$, $p < .05$].

As for the training phase, when the mean RTs observed for responses at cluster boundaries were compared with the mean RTs for responses within cluster boundaries, the former proved longer than the latter [$t(15) = 2.14$, $p < .05$].

Overall, the results obtained in Experiment 2 corroborated the finding of the previous experiment. The analysis of the results obtained from the training phase replicated the results obtained in Experiment 1 with longer RT observed at cluster boundaries compared to RT for responses corresponding to ordinal steps within cluster boundaries, and the response initiation time showing the longest latency. Thus, as the pattern of results observed in Experiment 1 was replicated in the training phase of Experiment 2 using different sequences, it appears to be very robust.

However, the most informative results were obtained in the testing phase where, as the participants were required to perform a single pointing response per trial, and which consisted in the identification of the next step in sequence, the length of the movement required for each response did not vary systematically for responses at cluster boundaries and within cluster boundaries. In this phase too clear differences emerged between responses at cluster boundaries and within cluster boundaries with the former taking significantly more time to perform than the latter. This is consistent with the hypothesis that when required to identify a step in the sequence located at cluster boundaries, the participants had to access a higher level of the representation of the sequence.

4. General discussion

The aim of the present study was to address the relatively unexplored issue of the role played by spatial structure in serial memory for locations. More specifically, it dealt with the issue of the role played by grouping by spatial proximity in the formation of hierarchical representations which enable the reduction of the demands associated with remembering sequences of nine ordinal steps.

The results of Experiment 1 confirm that in a task resembling Corsi's tapping test participants' ability to reproduce nine-step sequences benefits from the presence of structure such as spatial clustering, when the sequences to be reproduced afford grouping by spatial
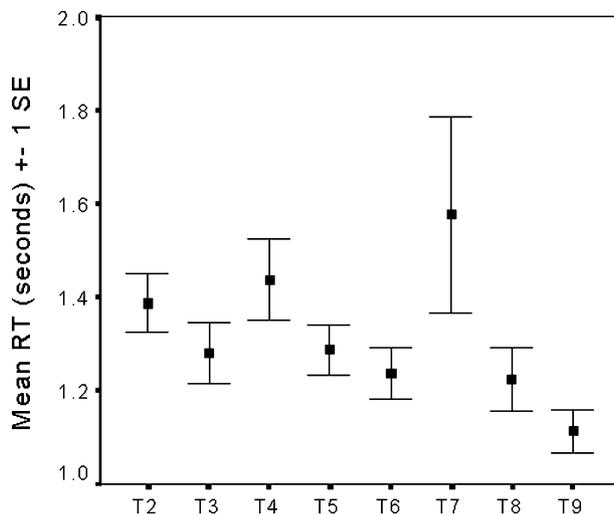

Fig. 7. Mean RT and standard error observed in the testing phase (single pointing response indicating the next step in the sequence) of Experiment 2 for responses corresponding to different ordinal steps (T2–T9) in the sequence. Results obtained for Sequences A, B, and C were combined for the analysis. T4 and T7 correspond to responses at cluster boundaries.

proximity. In fact, a higher level of accuracy was observed in sequences segregated by spatial clusters and that could be represented hierarchically.

The notion that participants developed a hierarchical representation of sequences segregated by spatial clusters was supported by the observed longer RT for responses at cluster boundaries compared to responses within cluster boundaries. In other domains this pattern of latencies has been traditionally associated with psychological chunking (Gobet et al., 2001; Klahr et al., 1983, Terrace, 1987, 1991). Since Corsi-type tasks seem to tap onto relatively pure spatial components of working memory (Della Sala et al., 1999; Logie, 1995; Logie & Pearson, 1997; Reisberg & Logie, 1993; Salway & Logie, 1995) the patterns of RT that emerged in Experiment 1 suggest that a similar forms of hierarchical organisation might pertain to the spatial domain as well.

Nevertheless, since in Experiment 1 the effect on response timing deriving from the use of a hierarchical representation was potentially confounded by effects produced by movement length, strong conclusions were not warranted by the results obtained there which could only be taken as suggestive of the notion that a hierarchical representation was actually underpinning performance.

The results of Experiment 2 corroborated the results of Experiment 1 by showing that, in conditions where the length of the movement required to perform a tapping response did not vary systematically with the spatial separation of the icons on the screen, responses at cluster boundaries still showed longer RT than responses corresponding to ordinal steps located within cluster boundaries. As such, the results of Experiment 2 provide stronger evidence for the notion that people do use spatial proximity in order to form hierarchical representations which aid performance in a serial spatial task.

The results of the experiments presented here provide only an initial indication that forms of organisation in serially ordered information, so far identified in other domains, might apply to spatial memory too. They are neutral in respect to the specific type of hierarchical organisation involved. In fact the results are compatible with a model such as that proposed by Sternberg and co-authors (Sternberg et al., 1988; Sternberg et al., 1990; Wright, 1990) as well as models where hierarchical organisation is based on the relative associative strength of items within and between chunks (see Gobet et al., 2001, for a review). In tasks requiring the reproduction of sequences of responses, such as the procedure featured here in Experiment 1 and the training phase of Experiment 2, moreover, it is difficult to isolate the effects produced by the organisation of the material in memory and the structure of the motor plan responsible for the execution of the sequences of tapping responses (see also Fischer, 2000, for a discussion of this point). As such, although the results obtained from Experiment 1 and

the training phase of Experiment 2 suggest that hierarchical organisation underpins performance, it is not possible to determine whether such organisation pertains specifically to the memory representation of the sequence, to the organisation of the motor output, or both. Nevertheless, the fact that evidence for hierarchical organisation emerged also in the testing phase of Experiment 2, where a single response was required, indicates that the memory component of the task may conform to a hierarchical principle of organisation independently from components responsible for the motor preparation of a series of tapping responses.

Concerning the possible involvement of other forms of representation and memory processes in the reproduction of spatially structured sequences, the present study did not assess directly the potential role played there by imagery and mental scanning. This would be an important issue to clarify since, in conditions similar to those featured in Experiment 2, the scanning of a spatially clustered mental image could also produce increased response times for responses located at cluster boundaries. However, a process entirely based on mental image scanning would not be able to explain the difference in performance between conditions featuring sequences segregated by clusters and sequences not segregated by clusters observed in Experiment 1. As such, the pattern of results obtained in this study could not be accounted for on the basis of a mental scanning hypothesis alone.

Finally, it is also worth noting that additional rule based organising factors that exploit the amount of redundancy present in different sequences would be necessary to account for the difference in performance observed between any two different sequences that are both segregated by clusters, such as Sequence A and Sequence B of Experiment 1.

Further research will be needed to identify other response parameters that would help in characterising how structured sequences are represented in spatial memory and how the spatial structure of the material to be remembered can be used strategically to minimise memory load.

It seems, nevertheless, that efforts along these lines would be well spent not only for the theoretical relevance inherent to the identification of the role played by spatial structure in serial temporary memory, but also for the potential clinical applications of investigations of the role played by spatial structure in the reproduction of tapping sequences.

As Corsi's test, a task upon which Experiments 1 and 2 were modelled, is widely used in neuropsychological research, it is not implausible to conjecture that the use of variants of the test which feature structured material might enable the detection of specific deficits which do not necessarily emerge when brute memory span is measured but might reveal important processing differences between healthy participants and participants

whose cognitive deficits are specifically localised in an inability to use the structure of the material at hand. The use of tapping tests featuring structured material might, for example, help to understand whether deficits in the ability to use strategically the structure of non-spatial information shown by frontal patients (see for example Stuss, Alexander, Palumbo, Buckle, & Pogue, 1994) might apply to serial-spatial memory as well.

Acknowledgments

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