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THE ROLE OF STRUCTURE IN AGE-RELATED INCREASES IN VISUO-SPATIAL WORKING MEMORY SPAN

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There is an important debate in the literature about the possible causes of developmental increases in working-memory span scores. In the present study, we tested the role of structure in relation to the age-related increases in visuo-spatial span performance. To that end, children and adults between nine and nineteen years old conducted structured and unstructured versions of the Corsi blocks task. All age groups performed better on structured than on unstructured paths, which indicates that working-memory control processes recruit resources such as long-term memory knowledge in performing the visuo-spatial span task. Interestingly, older participants benefited more from the presented structure than did younger participants, indicating that the structured presentation of sequence paths enhances the development of visuo-spatial span performance. Additional analyses showed that the effect of structure was not attributable to other path characteristics such as the path length or the number of path crossings. Implications of the present findings for views on the development of visuo-spatial working memory are discussed.

Introduction

There is no doubt about the improvement of working-memory span performance across age. However, the possible causes of this increasing performance are still poorly understood – and this is especially true for the visuo-spatial component of working memory. The goal of the present study is to investigate the role of one possible cause of age-related improvement in visuo-spatial span performance. More specifically, we test whether structural information, stored in long-term memory, plays a significant role in the development of visuo-spatial span performance.

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Working memory

Working memory serves the "moment-to-moment monitoring, processing, and maintenance of information" (Baddeley & Logie, 1999, p. 28). One of the most influential views on working memory is based on the multi-componential working-memory model of Baddeley and Hitch (1974; see also Baddeley, 1986), consisting of a central executive component that supervises two specialised slave systems which deal with different modalities of information. The first slave system is the phonological loop, which is responsible for the manipulation and the short-term maintenance of verbal information. The second slave system is the visuo-spatial sketch pad, which fulfils a similar role for visuo-spatial information. More recently, Baddeley (2000) added a fourth system to the working-memory model, the episodic buffer, which provides a temporary interface between the two slave systems and long-term memory.

The development of visuo-spatial working memory

Children's performance on visuo-spatial working-memory tasks increases with age. This has been found for the Corsi blocks task (a two- or three-dimensional task where block sequences have to be reproduced), the visual patterns task (a task where two-dimensional matrices have to be remembered), the Mr. Peanut task (a task where the positions of dots on a clown figure have to be remembered), and a probed-memory task for spatial locations (see Kemps, De Rammelaere, & Desmet, 2000; and Pickering, 2001, for review). There is, however, hardly anything known about the possible *causes* of the developmental changes in visuo-spatial working memory. That is, we do not know in which ways adult capacities to store and manipulate visuo-spatial material emerge across the childhood period. One factor that might help to perform better on visuo-spatial working-memory tasks is the phonological recoding of visuo-spatial stimuli.

Phonological recoding

When presented visuo-spatial stimuli, both children (from about the age of 8) and adults often recode them into a phonological format. Phonological recoding of visuo-spatial stimuli offers the possibility to use both visual and verbal codes. This dual coding strategy is very useful as it improves the recall of visuo-spatial stimuli (Paivio, 1971; Palmer, 2000). Although this strategy might improve visuo-spatial working-memory performance, it is quite questionable that the development of visuo-spatial working memory can be completely attributed to changes in the use of phonological recoding. First, even though the development of visuo-spatial working memory is strongly related to the use of phonological recoding strategies, visuo-spatial codes are not abandoned completely during development. Visuo-spatial coding continues to play a role in visuo-spatial working-memory processes, even after the phonological coding strategy has been acquired (Brandimonte, Hitch, & Bishop, 1992; Della Sala, Logie, Marchetti, & Wynn, 1991; Hitch, Woodin, & Baker, 1989; Logie, Della Sala, Wynn, & Baddely, 2000). Furthermore, Kemps et al. (2000) observed no interference of articulatory suppression on children's Corsi block performance, which indicates that children can perform the task solely relying on non-verbal working-memory resources. Verbal coding does not play a role in adults' Corsi block performance either (e.g., Farmer, Berman, & Fletcher, 1986), at least not in the forward version of Corsi blocks task (Vandierendonck, Kemps, Fastame, & Szmalec, 2004). Consequently, as Pickering (2001) argues, the developmental improvement in children's visuo-spatial working-memory performance is not entirely conditional upon the use of phonological encoding strategies.

In the present study, we investigate whether the presentation of visuo-spatial structures – which are very difficult to encode verbally – improves visuo-spatial working-memory performance. As explained further, visuo-spatial structures comprise several Gestalt principles such as symmetry, repetition and continuation. As a consequence, structured paths are redundant (i.e., subsequent blocks can be predicted from preceding blocks) whereas unstructured paths are not redundant. We also examine whether the role of such visuo-spatial structures changes through development. One mechanism that might take advantage of structure is chunking.

Structure and chunking

Chunking is an information-processing mechanism by which information is grouped or reorganised into familiar or regular structures. Because each 'chunk' collects a number of pieces of information from the environment into a single unit, chunking generally leads to an increased ability to extract information from the environment, in spite of constant cognitive limitations (Gobet, Lane, Croker, Cheng, Jones, Oliver, & Pine, 2001). The grouping process of chunking thus reduces the quantity of information that must be held in working memory (Cowan, 1997). An example of chunking in the visuo-spatial domain is encoding a six-block sequence of the Corsi blocks task as two three-block sequences. In doing so, the nature of the representation that is held in working memory is altered (Pickering, 2001). An early but very nice study which underlined the role of structural long-term memory knowledge in visuo-spatial working memory tasks was conducted by de Groot (1965; see also Chi, 1978). In this study, participants' ability to recall chessboard configurations was investigated in relation to their knowledge of chess. Participants who were experienced chess players were better at recalling the location of pieces on the board, but only when pieces were arranged in legitimate configurations.

The role of structure in visuo-spatial working-memory tasks in adults

Until recently, the potential importance of structure imposed on the Corsi blocks task received very little attention. One of the first to enter this unexplored domain was Kemps (1999, 2001). Using a 25-blocks-variant of the Corsi blocks task, she investigated complexity effects on adults' visuo-spatial working memory performance. The complexity of the paths (i.e., a sequence of blocks) was determined by a quantitative factor (the number of blocks) and a structural, qualitative factor (the positioning of the blocks). Performance was better when the number of blocks was smaller, but also when the paths were structured. Kemps (2001) further observed that the effects of structure remained, even when the mechanisms for visuo-spatial coding were taxed by a secondary visuo-spatial task. More recently, it has been shown that the effects of structure remain even when phonological or executive working-memory resources are taxed (Rossi-Arnaud, Pieroni, & Baddeley, 2006). It is therefore concluded that the superiority of recall of structured over unstructured paths does not only depend on visuo-spatial working memory, but that it is also aided by long-term knowledge of structure. Hence, recall of structured paths is better as it reflects the contribution of both working memory and long-term memory. The poorer recall of unstructured paths, in contrast, suggests that these paths do not comprise long-term memory structural representations.

De Lillo (2004) also investigated the role of structure in adults' visuo-spatial working-memory performance. He used a 9-blocks-variant of the Corsi blocks task consisting of three 3-blocks clusters. The to-be-remembered paths could be spatially clustered or non-clustered. De Lillo observed better performance when the paths were spatially clustered than when they were not. Moreover, response times were longer between clusters than within. The structure presented in the paths helped participants to hierarchically recode long sequences into shorter sub-sequences, with as consequence a better performance for spatially structured paths than for unstructured paths. In sum, Kemps (2001), De Lillo (2004), and Rossi-Arnaud et al. (2006) were the first to show the importance of structure as memory offloading device in visuo-spatial span tasks.

Goal and hypotheses

The aim of the present research was to investigate the role of structure in the *development* of visuo-spatial working-memory performance. The Corsi blocks task was chosen as task of interest. The Corsi blocks task is one of the most important visuo-spatial tasks, and has accordingly been used extensively in many clinical and experimental studies for over 30 years (see Berch, Krikorian, & Huha, 1998, for a review). The task was originally designed by Corsi (1972), and consisted of a series of nine blocks arranged irregularly on a 23 x 28 cm wooden board. The blocks are tapped by an experimenter in randomized sequences of increasing length. Immediately after each tapped sequence, the participant attempts to reproduce it, progressing until no longer accurate.

We opted for a modified version of the Corsi blocks task for two reasons. First, because the sequence paths are not easily encoded verbally (e.g., Farmer et al., 1986; Milner, 1971), Corsi-like tasks tap primarily onto spatial working-memory subcomponents (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Logie, 1995; Logie & Pearson, 1997; Reisberg & Logie, 1993; Salway & Logie, 1995; Vandierendonck et al., 2004). Second, it is a task for which structured and unstructured paths can be developed (Kemps, 1999, 2001) and it thus provides possibilities to assess the role of structural information in the development of visuo-spatial working memory performance.

The construction of different path types also raises another unresolved issue in the domain of visuo-spatial working memory. That is, very little is known about the impact of path characteristics (e.g., path crossings, path length, et cetera) on visuo-spatial span performance (but see Parmentier, Elford, & Maybery, 2005). As will be outlined further, the sequence paths used in the present study not only allowed us to test the role of structure; they also allowed us to measure the impact of other parameters of path configuration. That is, we tested whether the superior performance on structured as compared to unstructured paths was really caused by the structure of the paths rather than by other path characteristics such as path length or the number of path crossings.

To investigate whether structural information might improve visuo-spatial working memory performance through development, structured and unstructured paths of the Corsi blocks task were administered to children and adolescents of different age groups. More specifically, we tested the age range from 9 to 19 years old. We decided to start at 9 years old, because still younger children may experience difficulties with the difficult, unstructured paths. The decision to test people up to 19 years old was based on recent studies showing prolonged development of visuo-spatial span into adulthood. Moreover, there are very few studies that have assessed visuo-spatial working memory up until adolescence (i.e., between the ages of 12 and 20 years old). It was expected that, if knowledge of structural information would help to retain visuo-spatial stimuli, older participants would perform better than younger ones especially on the structured paths. Consequently, since knowledge of structural information grows with age, the difference between structured and unstructured paths was expected to grow larger with age.

Method

Participants

Seventy-two persons between 9 and 19 years old participated in this study. They were divided into six age groups of twelve persons each. The six age groups consisted of 9-year-olds (mean age 9 years 2 months), 11-year-olds (mean age 11 years 3 months), 13-year-olds (mean age 13 years 7 months), 15-year-olds (mean age 15 years 7 months), 17-year-olds (mean age 17 years 6 months), and 19-year-olds (mean age 19 years 3 months). In each age group there were six males and six females. All 9 to 17 year old children were recruited from schools for children with a normal intelligence; the 19-year-olds were university students. None of the participants had prior experience with the Corsi blocks task.

Materials

We used a three-dimensional version of the Corsi blocks task, in which twenty-five blocks (4 x 4 x 4 cm) were positioned on a black wooden board (40 x 40 cm) in a 5 x 5 matrix. The blocks were numbered from 1 to 25; these numbers were visible by the experimenter, but not by the participants. The nature of the task format (i.e., the 5 x 5 grid) is highly regular and therefore lends itself to the construction of spatial relations among the blocks. We used exactly the same paths as Kemps (2001). The path structure was determined by three Gestalt principles: symmetry, repetition and continuation. Structured paths comprised at least one of these principles. Examples of these paths are shown in Figure 1a. Unstructured paths did not comprise any of these principles, and were in no way redundant; examples of these paths are shown in Figure 1b. The results of a test in which people had to rate the structure of the paths can be found in the Appendix. These results show that our manipulation of structure was successful at the different path lengths.

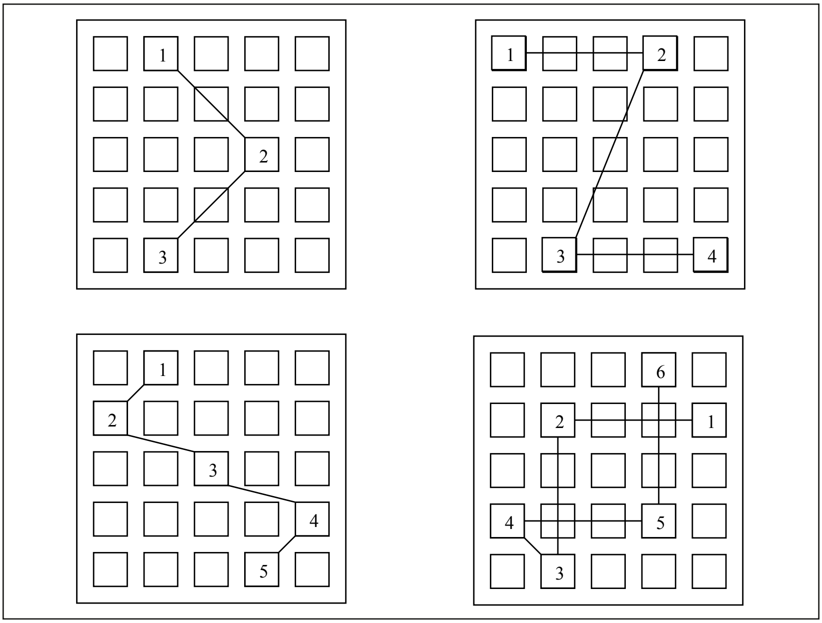

Figure 1a
Examples of structured paths

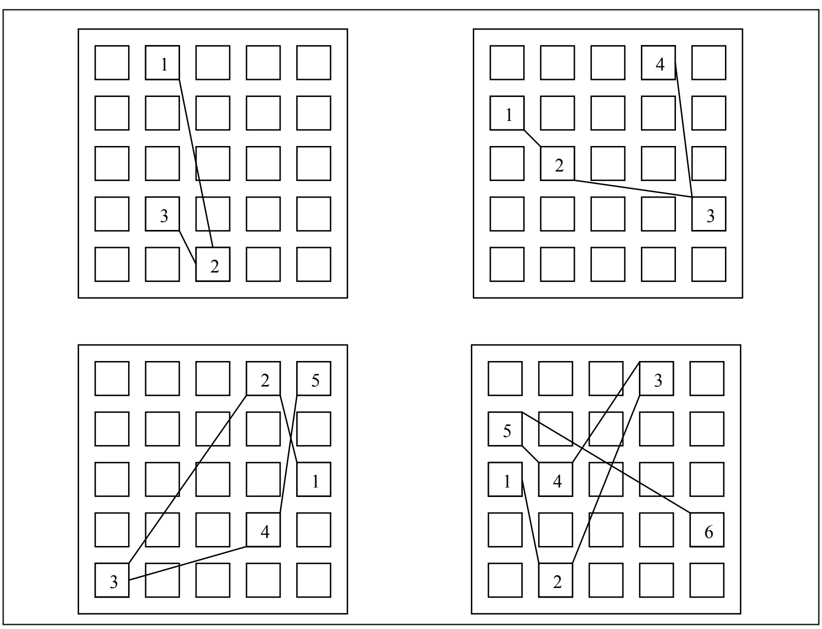

Figure 1b
Examples of unstructured paths

Procedure

Participants were tested individually in a quiet room. They were given instructions about the task and conducted a few practice trials. The experimenter touched a series of blocks at a rate of one block per second. Subsequently, the participant was required to touch the blocks in the same order of presentation. Per path-length (three up to eight blocks), participants were given three structured and three unstructured trials in a randomized order. If two out of the three trials were repeated correctly, the path-length was increased by one. When the participant failed on two or more trials of a given path-length for both the unstructured and the structured paths, the experiment was ended. For both the structured and the unstructured paths, each correct trial counted as one third; the total number of thirds was added and incremented with two in order to provide a span score (Smyth & Scholey, 1992). This measure is more sensitive than the simpler alternative of taking the individual span as the longest sequence length for which two out of three sequences are correctly recalled.

Results

A 6 (Age: 9, 11, 13, 15, 17, 19) x 2 (Structure: structured vs. unstructured) analysis of variance was conducted on the average memory spans (see Figure 2). The reported results are considered to be significant if $p < .05$. Both main effects were significant. Structured paths were recalled better than unstructured paths, $F(1, 66) = 210.53$ ($\eta_p^2 = 0.76$). The main effect of Age, $F(5, 66) = 8.01$ ($\eta_p^2 = 0.11$) indicates that the memory spans of older children were significantly higher than those of younger children. A planned linear trend comparison confirmed that the memory spans increased linearly across age, $F(1, 66) = 36.72$ ($\eta_p^2 = 0.36$). Further planned comparisons showed that the age-related increase in span was significant for both unstructured, $F(1, 66) = 23.33$ ($\eta_p^2 = 0.26$) and structured paths, $F(1, 66) = 37.70$ ($\eta_p^2 = 0.36$). The interaction between Structure and the linear contrast for Age indicated that the age-related rise in performance was higher for the structured than for the unstructured paths, $F(1, 66) = 11.69$ ($\eta_p^2 = 0.15$). Stated differently, the older participants benefited more from the structure than did the younger ones.

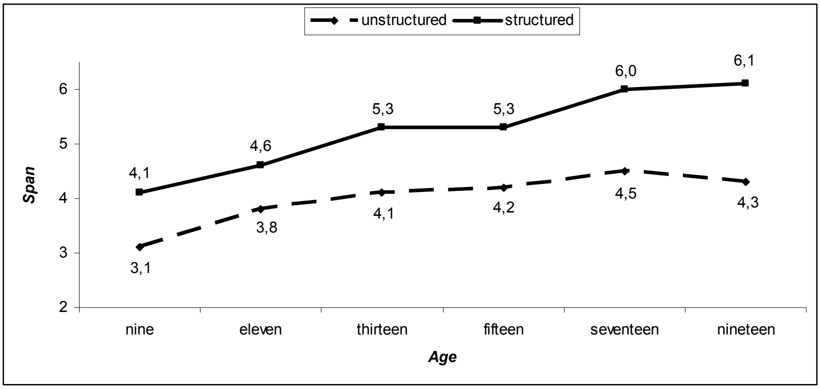

Figure 2
Mean memory spans as a function of Age and Structure

As noted above, the data gathered in the current study also allow us to test the effect of several path characteristics. Earlier studies mainly concentrated on only one path characteristic, i.e., the number of blocks. There are, however, many other factors that may influence people's performance on the Corsi blocks task. Indeed, the analysis above shows large performance differences between structured and unstructured paths with the same number of blocks. The goal of the analysis below was thus twofold. First of all, it is a test of the possible influence of various path characteristics on visuo-spatial span performance – an issue that has been overlooked in previous studies but that is highly relevant for further studies in the domain of visuo-spatial working memory. Second, it is a test of whether the effect observed above (i.e., better performance on structured than on unstructured paths) is really attributable to the structure of the paths, and not to other (possibly confounding) path characteristics.

A hierarchical regression analysis was performed with the score per path (collapsed over participants) as dependent variable. The number of crossings, the number of blocks, and the path length (i.e., length of the path defined by the sequence, not the number of blocks) were added in the first stage, and the structure of the path (dummy coded) was added in the second stage. Altogether, the first three factors explained a reasonable amount of variance (R^2 = .851). The path score was predicted by the number of blocks (standardised *Beta* = -.829, indicating lower scores for more blocks), but not by the number of crossings or the path length (each $p > .05$). The more important question, however, is whether the path structure explains extra variance in the span score when controlling for the other three factors. This was the case: the path structure accounted for 5.2% additional variance (R^2 = .903), *F change*

(1, 67) = 36.06. The standardised *Beta* for the path structure was .274 and indicates that span scores were higher for structured than for unstructured paths. This additional analysis clearly shows that the effects of Structure cannot be reduced to mere difficulty effects such as the number of crossings, the number of blocks, or the path length. Moreover, it demonstrates that both short and long paths can take advantage of structure.

Discussion

The development of visuo-spatial memory span

The main purpose of this research was to investigate the role of structure in the development of visuo-spatial span performance. The results demonstrated that visuo-spatial span grows with age and that the memory span is larger for structured than for unstructured paths. Larger span scores for structured than for unstructured paths were found in all age groups. The presence of structure in visuo-spatial stimuli is thus beneficial for children and adolescents in the age range from 9- till 19-year old. Even the youngest ones performed significantly better on structured paths than on unstructured paths. More importantly, the difference between structured and unstructured paths grew larger with age. Older participants performed better than younger ones, and this difference was most apparent on structured paths. Thus, particularly the structured paths enabled older participants to achieve higher visuo-spatial span scores. When structure occurs in visuo-spatial working-memory tasks, older participants were able to make better use of this structure than younger ones.

The present results also disconfirm the idea that visuo-spatial span performance reaches an adult level of achievement around 14 years old. Actually, our data show that visuo-spatial working memory and perceptual processing continue to improve up to late adolescence, which is in agreement with other recent studies (e.g., Gathercole, 1999; Kovacs, 2000; Luciana, Conklin, Hooper, & Yarger, 2005; Luciana & Nelson, 1998; Mondloch, Geldart, Maurer, & de Schonen, 2003; Zald & Iacono, 1998). The protracted development of visuo-spatial working memory has recently also been confirmed on a more neurological level. Kwon, Reiss, and Menon (2002) observed age-related increases in prefrontal cortical activation – associated with visuo-spatial working memory – from 7-year olds to 22-year olds. Swanson (1999) even observed increases in visuo-spatial working memory until ages 35-40, at which point span scores start to decline. He further argues that the amount of activation of long-term structures changes with age, which is – as will be argued below – also what our data showed.

So why does structure increase the performance on visuo-spatial working memory tasks? We do not believe that the effects observed in the present study are purely perceptual ("bottom up processes"). The regression analysis confirmed that the effects of Structure cannot be reduced to a better memory for 'easy' paths (i.e., short paths with only a few crossings) than for 'hard' paths (i.e., long paths with lots of crossings). In our view, two mechanisms may play an important role (see also Pickering, 2001): (1) changes in the contents of long-term memory, and (2) changes in processing strategies.

First, structures have to be stored in long-term memory before they can be used in working-memory tasks. As they grow older, children must gradually assemble information about visuo-spatial features of their environment before they will be able to discover structure. During this process – that is enhanced by experience and education – children construct multiple representations of various visuo-spatial structures in their long-term memory. These representations can then be used in subsequent situations. Consequently, as older children have a broader visuo-spatial knowledge about the world, they benefit more from structured paths than younger children.

Also note that earlier research by Kemps (2001) suggested that adults' superiority for recall of structured over unstructured paths could be supported by long-term knowledge of structure. The pattern of results observed by De Lillo (2004) also indicates that participants spontaneously construct a hierarchical representation that is based on spatial structures observed in the working memory task but stored in long-term memory. This reasoning fits well with the view of working memory as a workspace where representations activated from the long-term memory, are manipulated, processed, rehearsed, or retained for immediate use (e.g., Beschin, Cocchini, Della Sala, & Logie, 1997; Conway & Engle, 1994; Cowan, 1993; Ellis, Della Sala, & Logie, 1996; Engle, 1996; Logie, 1995, 1996; Stoltzfus, Hasher, & Zacks, 1996). Visuo-spatial information first activates visuo-spatial representations in long-term memory, which subsequently become available to visuo-spatial working memory ("top down" processes).

The present results may also uncover some information about the interactions between working memory and long-term memory. Our study showed that acquired knowledge (stored in long-term memory) may contribute to the development of working memory. In previous studies, it has been shown that a well developed working memory is necessary to acquire knowledge stored in long-term memory (e.g., Gathercole & Pickering, 2000a, 2000b). When both approaches are taken together, an important interaction between long-term memory and working memory becomes evident. On the one hand, working memory promotes the development of long-term memory; on the other hand, stored knowledge promotes the development of a well functioning working memory.

A second mechanism that helps to explain the role of structure is the use of *strategies*. Across their development, children gain understanding in strategies, resulting in more frequent and more efficient strategy implementation (e.g., Cowan, 1997; Schneider & Sodian, 1997). Thus, it is not only the availability of structural information in long-term memory that is crucial; the strategy deployment of these long-term memory representations is as important. Of the two major forms of processing strategies (i.e., organisation and rehearsal, Goswami, 1998), structured visuo-spatial information might especially enhance the organisation strategy. Indeed, structural features may invite children to use a better-organised strategy (e.g., chunking) in order to retain the to-be-remembered path. Since the chunking strategy reduces working memory load, a better performance on visuo-spatial working memory tasks is obtained. The use of strategies is an underexplored aspect of visuo-spatial working memory (see also Fisher, 2001) and definitely deserves more attention in future studies.

Whichever of the two mechanisms is the most crucial, the question remains of *how* the structural representations, stored in long-term memory, are integrated with the visuo-spatial information presented in the working memory task. A very suitable candidate for this integrating process is the episodic buffer (Baddeley, 2000), which binds and integrates information from the slave systems and information from long-term memory. Another capacity of the episodic buffer is binding information into chunks – which was exactly what our participants did with the structural block sequences.

The importance of path characteristics

The present study also tested the impact of various path characteristics on visuo-spatial span performance – an often overlooked issue. We observed that neither path length nor path crossings affected people's visuo-spatial span performance. This is in agreement with the data obtained by Smyth and Scholey (1994), who observed no effect of path length on visuo-spatial span performance. However, there is a difference between our results and those obtained by Parmentier et al. (2005), who did observe effects of path length and path crossings on visuo-spatial span performance. It is possible that the discrepancy between our study and Parmentier et al.'s is due to the type of task: the present study used a Corsi-like task whereas Parmentier et al. (2005) used a task in which sequences of black dots appeared in quasi-random locations on a computer screen. Moreover, the position of the dot patterns changed every trial whereas the background in the Corsi blocks task remained identical throughout the experiment.

Further research is thus needed to identify which aspects of visuo-spatial sequences affect the memory span performance. The fact that paths with the same amount of items (dots or blocks) do not always have the same level of difficulty is intriguing and clearly shows that path characteristics are not irrelevant, but do affect people's visuo-spatial span performance. Researchers have to take this issue into account when using visuo-spatial working memory task in future studies. It would also be interesting to investigate whether the main conclusion of the present study (i.e., about the significant role of structure in the development of visuo-spatial working memory) holds when tested with purely visual tasks such as the visual patterns task. However, the reason for further research on path characteristics is not only methodological, but also theoretical: Understanding the influence of path characteristics on people's span performance should improve our understanding of (the development of) visuo-spatial working memory.

Conclusion and implications

The current study demonstrated that the presence of structure in visuo-spatial material improves performance on the Corsi blocks task – an effect that becomes even larger with increasing age. The data thus suggest that there are different stages in the development of visuo-spatial span performance. The dual-coding process, by which visuo-spatial stimuli are phonologically recoded, develops at the age of 8 already (Paivio, 1971; Palmer, 2000). The usage of long-term memory knowledge and higher-level strategies seems to develop more protractedly. Especially older children's and adolescents' visuo-spatial span performance seems to improve by the usage of long-term memory knowledge and more enhanced strategies. Future studies might investigate more specifically *when* and *how* the different processes such as dual coding, the usage of long-term memory knowledge, and the application of higher-level strategies occur and interact with performance on visuo-spatial working memory tasks.

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Appendix

In order to test the reliability of the variable 'Structure', forty-four first year psychology students (21 males, 23 females, mean age 19 years 1 month) were asked to rate the structure of the paths. All block sequences were randomly presented on a computer screen. One path presentation consisted of a series of blocks that turned into black at a rate of one block per second. The 5 x 5 grid remained visible on the screen. After each path, the participant had to rate the structure of the path on a Likert-like scale from 1 (not structured at all) to 9 (very structured) with a mouse click.

Table A
Mean ratings of structure as a function of Path length and Structure
Standard errors are shown between brackets

	3 blocks	**4 blocks**	**5 blocks**	**6 blocks**	**7 blocks**	**8 blocks**
Unstructured	2.38 (0.17)	2.79 (0.16)	2.70 (0.15)	2.62 (0.14)	2.92 (0.13)	2.92 (0.17)
Structured	6.52 (0.21)	6.07 (0.15)	5.21 (0.14)	5.07 (0.17)	5.90 (0.12)	6.89 (0.16)

A 6 (Path length: 3, 4, 5, 6, 7, 8 blocks) x 2 (Structure: structured vs. unstructured) analysis of variance was conducted on the average rating score (see Table A). Mean ratings were significantly higher for structured sequences (5.95) than for unstructured sequences (2.72), $F(1, 43) = 595.05$ ($\eta_p^2 = 0.93$), and this was true for each path length (each $p < .001$). A planned comparison showed that the difference between ratings for structured and unstructured paths did not increase linearly with the path length, $F(1, 43) = 1.92$ ($p = .17$). This shows that the increased use of structure with age, which we observed in the current study, is not confounded with path length.

The way in which structure was imposed did thus not offer greater advantages at the longer sequence lengths as compared to the shorter sequence lengths. Therefore, the older participants' greater reliance on structure is not caused by the fact that the older participants reach longer block sequences. Consequentially, age-related differences in the performance on structured versus unstructured paths can be safely interpreted and cannot be attributed to age-related differences in overall performance. To conclude, older children are better able to exploit structure than are younger children.

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