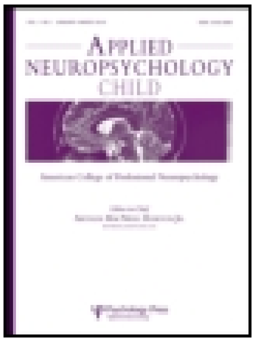

Applied Neuropsychology: Child

ISSN: 2162-2965 (Print) 2162-2973 (Online) Journal homepage: http://www.tandfonline.com/loi/hapc20

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http://dx.doi.org/10.1080/21622965.2016.1268960

Performance on tasks of visuospatial memory and ability: A cross-sectional study in 330 adolescents aged 11 to 20

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ABSTRACT

Cognitive functions mature at different points in time between birth and adulthood. Of these functions, visuospatial skills, such as spatial memory and part-to-whole organization, have often been tested in children and adults but have been less frequently evaluated during adolescence. We studied visuospatial memory and ability during this critical developmental period, as well as the correlation between these abilities, in a large group of 330 participants (aged 11 to 20 years, 55% male). To assess visuospatial memory, the participants were asked to memorize and reproduce sequences of random locations within a grid using a computer. Visuospatial ability was tested using a variation of the Design Organization Test (DOT). In this paper-and-pencil test, the participants had one minute to reproduce as many visual patterns as possible using a numerical code. On the memory task, compared with younger participants, older participants correctly reproduced more locations overall and longer sequences of locations, made fewer mistakes and needed less time to reproduce the sequences. In the visuospatial ability task, the number of correctly reproduced patterns increased with age. We show that both visuospatial memory and ability improve significantly throughout adolescence and that performance on both tasks is significantly correlated.

KEYWORDS

Adolescence; cognition; design organization test (DOT); development; nonverbal memory; visuospatial ability; visuospatial memory

Introduction

The brains and behaviors of children change enormously during the journey from childhood to adulthood (Crone, 2008, 2009). While areas associated with sensory and motor processes mature during early childhood, areas associated with more cognitive functions, such as top-down behavioral control, mature during the later stage of adolescence (Casey, Tottenham, Liston, & Durston, 2005; Giedd, Blumenthal, & Jeffries, 1999). This difference in maturational timing is reflected by the fact that for different cognitive tasks, an adult-like performance level is achieved at different points in development (Diamond, 2015; Luna, Garver, Urban, Lazar, & Sweeney, 2004). For instance, performance on a simple planning task, such as the three-disc Towers of Hanoi task, is already equal to adult performance by six years of age, but performance on tasks involving the implementation of sorting strategies do not reach an adult level until the age of ten (Welsh, Pennington, & Groisser, 1991). Recent research has shown not only that physical changes during childhood involve the strengthening of the neural network within certain areas but also that the network connecting different brain areas weakens (Sherman et al., 2014). Individual differences among children in brain maturation have been hown to be closely related to differences in intellectual functioning (Koenis et al., 2015). Additionally, training of intellectual performance, such as training working memory, has been shown to alter neural connectivity in the brain (Barnes, Anderson, Plitt, & Martin, 2014).

Performance on memory tasks is strongly dependent on several factors, including the domain, verbal, or nonverbal (Shipstead & Yonehiro, 2016); the task, recall or recall with data manipulation (Unsworth & Engle, 2007); and the form in which the data are presented, sequential or simultaneous (Carretti, Lanfranchi, & Mammarella, 2013). The difference between verbal and non-verbal is not determined solely by whether the elements to memorize are words or pictures. When elements that must be memorized can easily be phonologically represented (Unsworth & Engle, 2007), such as figures representing a geometrically explicit form (perhaps a “triangle” or “house”), active rehearsal is facilitated, and memory performance improves (Baddeley, 1986). To prevent this crossover between non-verbal and verbal domains, as in this study, visuospatial patterns that are very difficult, if not impossible,

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to represent phonologically are used. Many models have been proposed to describe the difference in performance between tasks. For example, Miyake, Friedman, Rettinger, Shah, and Hegarty (2001) support a model of working memory in which verbal and non-verbal information are handled by two distinct systems (Miyake et al., 2001). Another model suggests that three components contribute to working memory (Baddeley, 1986), with two of these components being domain-specific maintenance resources, verbal or non-verbal, and one domain-general attention resource involved in the control and regulation of the system (Shipstead & Yonehiro, 2016). This domain-general component has also been described as a mental workspace and as having a much broader functioning. In this model (Logie, 2003), the domain-general component allows for the organization and manipulation not only of elements stored in short-term memory but also of elements retrieved from long-term memory and elements generated by sensory inputs. The difference between the domain-specific and the domain-general memory has been shown to be larger in the verbal domain than in the nonverbal (visuospatial) domain (Miyake et al., 2001). This difference between domains suggests that tasks in the visuospatial memory domain place a larger demand on cognitive functioning than tasks in the verbal domain. The larger the demand on cognitive functioning is, the later performance increases in childhood (Cestari, Lucidi, Pieroni, & Rossi-Arnaud, 2007). Within the visuospatial domain, performance has also been observed to be better when elements are presented simultaneously rather than sequentially (Lecerf & de Ribaupierre, 2005), supporting the existence of sequential and simultaneous presentation-dependent processes in visuospatial working memory (Pazzaglia & Cornoldi, 1999). This division has further been confirmed in studies showing that individuals with Williams syndrome performed less well in spatial-simultaneous tasks but equally well in spatial-sequential tasks (Carretti, Lanfranchi, De Mori, Mammarella, & Vianello, 2015). A study with healthy children confirmed that a division of working memory between simultaneous and sequential spatial best describes their performance in tasks using these modalities (I. C. Mammarella, Pazzaglia, & Cornoldi, 2010). The differentiation of working memory into different processes is already in place in children from approximately 4 to 6 years of age (Hornung, Brunner, Reuter, & Martin, 2011) and studies with children up to eleven years of age have shown a sizable expansion in functional capacity during childhood (Alloway, Gathercole, & Pickering, 2006) and fifteen (Gathercole, Pickering, Ambridge, & Wearing, 2004). However, because cognitive function continues to mature until young adulthood (Casey et al., 2005; Crone, Wendelken, Donohue, van Leijenhorst, & Bunge, 2006), studying adolescent memory performance over the whole continuous age range of adolescence up to early adulthood is interesting, specifically in the non-verbal visuospatial domain. The maturation of cognitive functioning also suggests that the development of performance on visuospatial memory tasks may be correlated with the performance on other visuospatial tasks with a high demand on cognitive reasoning.

Many different tasks aim to measure visuospatial abilities, and performance on these tasks is often considered an important predictor of general intellectual abilities (Shea, Lubinski, & Benbow, 2001). “Visuospatial abilities” is a grouping of several different types of abilities. A long-used way of grouping (Linn & Petersen, 1985), proposes three categories of spatial tasks: spatial visualization, spatial perception, and mental rotation or, more generally, the mental manipulation of 2- and 3-dimensional objects (Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012). More recently, a different approach using a top-down analysis of the nature of spatial thinking has been suggested to arrive at a structure of spatial intellect (Uttal, Meadow, Tipton, & Hand, 2013) with a two-dimensional classification of the visuospatial tasks: intrinsic vs. extrinsic and static vs. dynamic (for a broad review of this classification scheme see Newcombe & Shipley, 2014). One of the better-known tests for visuospatial ability is the Block Design Test, which is a sub-test of the Wechsler Adult Intelligence Scale (Wechsler, 1981) and can be grouped in the “spatial visualization” (Linn & Petersen, 1985) and “static extrinsic” (Newcombe & Shipley, 2014) category. Performance on this test improves during adolescence (Shah & Frith, 1993). A similar increase in visuospatial abilities through late adolescence was shown using a variation of the simple pen and paper Design Organization Test (DOT: Burggraaf, Frens, Hooge, & van der Geest, 2015), which provides a faster and easier way for measuring visuospatial ability than the lengthy Block Design Test (Killgore, Glahn, & Casasanto, 2005; Killgore & Gogel, 2014). In recent years, a reason for differences in performance between the sexes has been suggested to be that men and women apply differential weighting to geometrical reference cues (Collaer & Nelson, 2002; Holden, Duff-Canning, & Hampson, 2015). However, these differences in visuospatial abilities by sex, have only been found in tasks involving mental rotation (Linn & Petersen, 1985; Voyer, Voyer, & Bryden, 1995).

Although visuospatial abilities have been studied during the adolescent age period, some issues remain to be elucidated. Firstly, visuospatial memory has often been studied in younger children (Alloway et al., 2006; Cestari et al., 2007; Heyes et al., 2012) and in small groups, with performance collapsed and averaged over various age ranges (Conklin, Luciana, Hooper, & Yarger, 2007; Gathercole et al., 2004) and. More specifically, results of participants with an age in the latter part of adolescence, if at all represented, are mostly grouped together with young adults (Luciana & Nelson, 2002; Rowe, Hasher, & Turcotte, 2009; van Leijenhorst, Crone, & Van der Molen, 2007). This makes it hard to properly correlate visuospatial memory performance with age. Secondly, performance on visuospatial memory and other visuospatial tasks depend, to a more or lesser extend, on the executive control which matures up to young adulthood. Nevertheless a description of the correlation between these tasks for the full adolescence period has, to our knowledge, not been published. Previous studies into this correlation have focused on adult populations (Miyake et al., 2001) and small children (Giofrè, Mammarella, & Cornoldi, 2013). Finally, measures for memory capacity are usually rather coarse. For example, the often-reported memory span of the Corsi block-tapping task can only yield a capacity between two and eight with steps of one (Corsi, 1972). This makes small differences in memory performance hard to detect.

In this study, we investigate over the full range of adolescence (11–20 years) the correlation between age and both visuospatial memory performance and visuospatial ability as well as the correlation between performance on both tasks. By using a large, homogenous sample (330 participants, one school, homogeneous socio-economic background) and several measures with a higher resolution than are often used, we expect our task to be sensitive to the small, individual differences in performance among children of a similar age. Visuospatial memory was assessed using a computerized test requiring participants to memorize a varying number of locations, loosely inspired by the Corsi block-tapping task (Corsi, 1972). Computerized versions of visuospatial memory tasks advantageously facilitate group administration. These have been used before (Cornoldi & Mammarella, 2008; Kessels, de Haan, Kappelle, & Postma, 2002; Rowe et al., 2009; Vandierendonck, Kemps, Fastame, & Szmalec, 2004) and have been shown to provide memory span and error rates that are essentially analogous to those obtained using the physical version of the Corsi test (Brunetti, Del Gatto, & Delogu, 2014). We also increased the number of trials, providing a possibility for a finer scale of memory span measurements. Visuospatial ability was assessed using the one-minute variation of the DOT, which has been used previously to assess visuospatial ability in adolescents (Burggraaf et al., 2015). Similar to previous studies, we hypothesized that visuospatial ability would increase with age throughout adolescence. Based on results showing that visuospatial memory depends heavily on executive functioning (Miyake et al., 2001), which continues to mature during adolescence up to early adulthood (Giedd et al., 1999), and on findings showing that performance improves up to middle-adolescence (Alloway et al., 2006; Gathercole et al., 2004), we hypothesized that visuospatial memory performance would also continue to improve up to adulthood. Furthermore, we expected that performance on the two tasks would be correlated, independent of age, reflecting the correlation between the two tasks that was found in an adult population by Miyake et al..

Methods

Data concerning the performance on a visuospatial memory and a visuospatial ability task were collected in a correlational study with a cross-sectional design. Participant age ranged from 11 to 20 years. The results of each task were analyzed to explore a possible correlation with age as well as a possible correlation in performance on the two tasks, when corrected for age.

Participants

Students in all six grades of the secondary school Gemeentelijk Gymnasium in Hilversum, The Netherlands as well as students who had graduated from that school the year before were asked to volunteer for an experiment consisting of two visuospatial tasks. Students from this school all follow a broad educational program that included science, several languages and the social sciences. To be admitted to this school, students must score within the highest twenty percent of a national educational achievement test, the CITO, which is administered during the last grade of primary school. Therefore, the general intelligence of the participants was high compared to the general population. Inclusion

Table 1. Age and gender distribution of the population per schoolyear.

School year	*N* (% male)	Age-range	Mean age (*SD*)
1	56 (45%)	11.6–13.6	12.5 (0.4)
2	51 (59%)	12.4–14.3	13.6 (0.5)
3	65 (45%)	12.9–15.7	14.7 (0.4)
4	51 (53%)	14.6–17.3	15.7 (0.5)
5	43 (67%)	15.7–18.4	17.0 (0.4)
6	45 (62%)	16.5–19.1	18.0 (0.5)
Alumni	19 (68%)	18.0–19.9	19.1 (0.5)
Total	330 (55%)	11.6–19.9	15.3 (2.1)

criteria were: male and female subjects; ages 11–20; attending/attended aforementioned secondary school and having normal or corrected to normal vision. In total, 333 students were included. On the day of testing, three students were excluded for physical or psychological reasons, leaving 330 students performing both experiments. The experiment was conducted during school hours, and no incentives were provided. The study adhered to the Declaration of Helsinki, and all participants and their parents provided informed consent prior to the study (Table 1).

Visuospatial memory task

We used a computerized variation of the often-used Corsi block-tapping task (Corsi, 1972) to assess the participants' visuospatial memory (Kessels, van Zandvoort, Postma, Kappelle, & de Haan, 2000). During each trial of the visuospatial memory test, the participants were shown a grid of six-by-six squares on a computer screen and were asked to memorize a sequence of three to seven cued locations within this grid. After a short retention period, they were asked to reproduce the cued location without respect to temporal order. Computerizing the task made it possible to administer the task simultaneously to groups of participants and to measure the time each participant needed to reproduce each of the memorized sequences of locations. Furthermore, the variation required memorization of only the locations and not the temporal order, as is required in the Corsi task. Ultimately, all participants were presented with all trials of all sequence lengths. The sequence lengths per trial were not ascending or descending, rather sequence lengths were randomly mixed. This contrasts with the Corsi task, which starts with a trial with the shortest length of two cued locations and only increases the length if the participant answers correctly. After two wrong trials, the task is aborted. Thus, the participant has an idea of the length of the sequence to be expected and is only allowed two errors, whereas in our task, the participant can also attempt the longer sequences. This provided the possibility of establishing a more precise measurement of visuospatial memory span than is possible with the Corsi task. To be able to provide many different sequences of each of the used sequence lengths, the number of possible locations was increased from nine, as in the Corsi task, to 36.

Materials

All 36 trials were designed in advance by a computer program that created random sequences of locations to be cued. The authors visually evaluated all sequences and patterns and rejected sequences that were easily phonologically verbalizable. Four trials with a sequence length of three locations were created; eight trials were created for each of the sequence lengths of four, five, six and seven locations. The resulting 36 trials were then randomly ordered, mixing the sequence lengths. Finally, all participants were presented with these trials in the same order.

A custom Java script, which is available upon request, was used to run the experiment on a laptop. The participants were seated at a desk with the laptop screen 60 cm away. The laptop screen was a 15-inch screen with a 1366×768 resolution. The locations were squares of 2.3 cm, resulting in a 2.2° viewing angle per square at this distance. The distance between the squares was 0.3 cm. Thus, the total 6×6 grid of squares had a viewing angle of 12.9°. The participants could use a mouse or the laptop track pad to report their responses.

Procedure

Before the computer program was started, the consecutive steps of the task were verbally explained to the participant. The task instructions were as follows: "Reproduce the cued locations as completely and correctly as possible; the order is of no importance."

To verify that the participant understood the instructions, the task started with three practice trials. After these practice trials, the participant continued with the 36 experimental trials: 188 locations were cued in total. At the beginning of each trial, a black-bordered, six-by-six grid on a white background was projected on the screen. The participant started a trial at his/her convenience by pressing the spacebar, after which a sequence of three to seven different squares would change to blue, cueing the locations to be remembered. Each square was colored for 700 ms, and there was a 150 ms pause before the next square changed color. Half a second after the end of a sequence, the background changed to light grey, signaling the participant that he/she could start selecting the locations within the grid that he/she remembered being cued. The participant selected squares by clicking on them; once the square was clicked, it turned blue. Clicking on a square again unselected it. When the participant was content with the selected squares, he/she could conclude the trial by pressing the spacebar. The locations of the selected squares were saved along with the time it took the participant to select the squares. After the trial ended, all the squares turned white again, and the word "pause" was displayed while the computer program waited for the participant to press the spacebar again to start the next trial. The duration of the task, including the explanation and practice trials, ranged from 8 to 12 min.

Scoring and outcome measures

Scoring performance on visuospatial memory tasks can be completed in many different ways (for a broad review see (Conway, Kane, & Bunting, 2005)). In our study we determined the fraction of recall and fraction of false alarms over all trials using 'partial-credit' scoring, as described by Conway et al.. This means that a participant is rewarded a fraction of the points equivalent to the fraction of locations that has correctly been reproduced. Specifically, the fraction of recall was the fraction of all cued locations that were correctly reproduced, and the fraction of false alarms was the fraction of all selected locations that were not cued. We also determined two measures of memory capacity. First, we determined the visuospatial memory span, defined as the longest sequence of locations that was correctly reproduced at least once which is equivalent to the definition used in the Corsi block-tapping task (Corsi, 1972). Second, for each of the five different sequence lengths, we calculated the fraction of correctly reproduced sequences. Last, the reproduction time per trial was determined. The reproduction time was defined as the time between the moment the participant was able to start selecting locations until the moment the spacebar was pressed, finalizing the response. From the reproduction times per trial, we calculated the average reproduction time for each of the five different sequence lengths, as well as the overall average reproduction time across all trials.

Visuospatial ability task

We used a slightly shorter variation of the Design Organization Test (DOT) to assess the visuospatial ability of the participants. The DOT was developed by Killgore and colleagues (2005). The shorter variation we used has previously been used to assess visuospatial ability in adolescents (Burggraaf et al., 2015) and prevented a ceiling effect that was present in the original version of the DOT.

Materials

The DOT consists of two test forms and a practice form (Figure 1). In this task, participants fill in the empty squares of the form with the numbers that correspond to the patterns included in the key at the top of the page; each of these numbers corresponds to the pattern shown directly beneath it. In the original version of the task, participants had 2 min per form. Using a population similar to the one in this experiment, Burggraaf et al. (2015) showed that with this amount of time, many of the participants achieved the maximum score; therefore, they decided to shorten the time per form to one minute. This one-minute version of the DOT was determined to be an effective tool for measuring visuospatial abilities in adolescents. Therefore, we decided to use the same variation of the DOT.

Procedure

The task was verbally explained to each participant as follows: "Within one minute, fill out as many squares as possible using the numbers that correspond to parts of the pattern using the numerical code at the top of the page." These instructions were provided in conjunction with the completed example, and the participant was asked to fill out the rest of the squares on the example form without any time constraints. After affirming that the participant performed the task correctly, he/she was given exactly one minute to fill out as many squares as possible on form A. After a brief pause, another minute

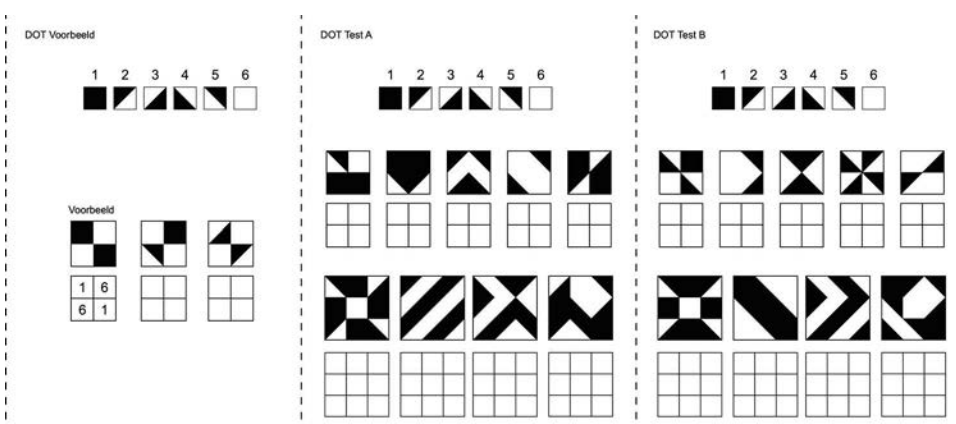

Figure 1. The Design Organization Test (DOT) consists of a practice form labeled 'DOT Voorbeeld' (which is Dutch for 'DOT example') and two forms labeled 'DOT Test A' and 'DOT Test B'. At the top of each form, each pattern is combined with a specific numerical code.

was given so that the participant could do the same for form B. The duration of the task, including the explanation and the completion of the practice form, was 5 to 6 minutes.

Scoring and outcome measures

The score (in points) for each participant was calculated as the mean number of correctly filled out squares in forms A and B. Similarly, each participant's number of mistakes (in points) was calculated by averaging the number of incorrectly filled in squares in forms A and B. Squares that were left empty were not considered.

Statistical analysis

Student's t-test was used to statistically assess differences in scoring and outcome measures between the sexes, and effect size was reported using Cohen's d. To determine the association between age and the scoring and outcome measures Pearson correlations were used. In order to assess the effect of sequence length on the fraction of correctly memorized sequences and on the average reproduction time per sequence length, a repeated measures ANOVA with one within-subject factor, sequence length (5 levels: 3–7 locations) was performed. Finally, we assessed the correlations between the score on the visuospatial ability task (DOT) and the five outcome measures of the visuospatial memory task (fraction of recall, fraction of false alarms, fraction of correctly memorized sequences per sequence length, visuospatial memory span, and mean reproduction time per sequence length) by running a partial Pearson correlation that controlled for age.

Results

All 330 included participants were able to complete both of the required tasks without any problems. Overall their ages were between 11.6 and 19.9 years ($M = 15.3$; $SD = 2.1$) 181 participants were male (55%; age 11.6–19.9; $M = 15.5$; $SD = 2.1$), and 149 participants were female (45%; age 11.6–19.4; $M = 15.0$; $SD = 2.0$).

Visuospatial memory task

Participants were given the choice of a computer mouse or a track pad to select locations, but all participants chose to use the computer mouse. After completing the task, four participants reported without specifically being asked that they had, at least once, accidentally pressed the spacebar after selecting zero squares or only one square. Such accidents could decrease the number of presentations of that sequence when we calculated the visuospatial memory span of those participants. Therefore, we checked the results of all participants, discarded the trials with zero responses or one response and corrected the number of trials presented accordingly. This resulted in the exclusion of 36 of the 11,844 trials.

The participants were able to correct their answers before ending a trial. The use of this option varied enormously across the participants—between 0 and 63 instances per participant over all trials; trials in which this option was used averaged 8.5 locations ($SD = 9.1$). Response speed was not mentioned in the instructions, but participants who were interviewed after the experiment explained that they had responded as quickly as possible so that they would not forget the sequence they had just seen.

The fraction of recall per participant ranged from 0.49–0.98 ($M = 0.80$, $SD = 0.08$) (Figure 2A); no ceiling effect was present. The fraction of false alarms ranged from 0.02–0.46 ($M = 0.19$, $SD = 0.08$). The fraction of recall did not differ between male and female participants ($M_{male} = 0.796$, $SD = 0.085$ vs. $M_{female} = 0.802$, $SD = 0.083$, resp., $t(328) = 0.63$, $p = 0.53$, Cohen's $d = 0.07$) and neither did the fraction of false alarms ($M_{male} = 0.188$, $SD = 0.081$ vs. $M_{female} = 0.186$, $SD = 0.080$; $t(328) = -0.23$, $p = 0.82$, Cohen's $d = -0.03$). The visuospatial memory span ranged from 3–7 locations, with a mean of 6.1 locations ($SD = 0.98$) and did not differ between the male and female participants ($M_{male} = 6.06$, $SD = 1.0$ vs. $M_{female} = 6.14$, $SD = 0.96$, resp., $t(328) = 0.66$, $p = 0.51$, Cohen's $d = 0.07$). The fraction of recall and the visuospatial memory span were very strongly correlated (Pearson's $r = 0.71$, $p < 0.001$).

As expected, the longer sequences were correctly reproduced less often than the shorter sequences (Table 2). Repeated-measures ANOVA was used to analyze the effect of sequence length on the fraction of correctly reproduced sequences and revealed a significant difference between the fraction of correctly reproduced sequences for the different sequence lengths ($F(4) = 1547$, $p < 0.001$, $\eta^2 = 0.825$). A post hoc test showed that for all sequence length combinations, except those with six and seven cued locations, the fraction of correctly reproduced sequences was highly significantly different (sequence length six and seven: $t = 1{,}0$, $p = 0.86$; for all other combinations, t varied between 15.4 and 65.9, $p < 0.001$). The mean reproduction time per trial varied between 4.3 s and 11.8 s ($M = 6.9$, $SD = 1.4$), and as expected, the reproduction of longer sequences took more time than the reproduction of shorter sequences (Table 2) ($F(4) = 864$, $p < 0.001$, $\eta^2 = 0.724$). A post hoc test showed that the

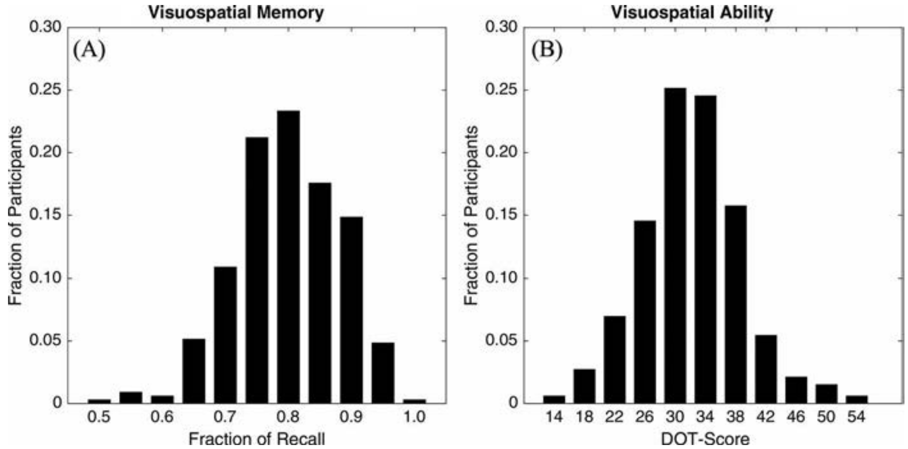

Figure 2. Frequency distribution of the participants' performance. A: Fraction of recall on the visuospatial memory task. B: Score on the visuospatial ability task (DOT).

Table 2. The correlation between age and the fraction of correctly memorized sequences and between age and the average response time per sequence (all $p < 0.002$).

Sequence length	Fraction of correctly memorized sequences mean (SD)	Change per year [95% confidence interval]	Pearson's r	Average response time (s) mean (*SD*)	Change per year [95% confidence interval]	Pearson's r
3	0.91 (0.16)	0.013 [0.005, 0.022]	0.17	4.57 (1.29)	−0.17 [−0.23, −0.10]	−0.27
4	0.62 (0.21)	0.035 [0.025, 0.046]	0.35	5.55 (1.23)	−0.19 [−0.25, −0.13]	−0.32
5	0.45 (0.23)	0.034 [0.023, 0.046]	0.31	6.57 (1.47)	−0.21 [−0.28, −0.14]	−0.30
6	0.17 (0.18)	0.021 [0.012, 0.030]	0.24	7.88 (1.85)	−0.18 [−0.28, −0.09]	−0.20
7	0.16 (0.19)	0.025 [0.016, 0.034]	0.28	8.73 (2.16)	−0.19 [−0.30, −0.08]	−0.18

reproduction times for all sequence length combinations were highly significantly different (with t varying between 10.1 and 51.3, all $p < 0.001$).

Visuospatial ability task

The mean score on the DOT of all 330 participants was 32.3 points ($SD = 6.7$). The scores ranged from a minimum of 13 to a maximum of 56 (Figure 2B). Only one participant attained the maximum attainable score. An independent samples t-test showed that the scores of the male ($M = 32.9$, $SD = 6.6$) and female participants ($M = 31.6$, $SD = 6.8$) did not significantly differ ($t(328) = -1.7$, $p = 0.10$, Cohen's $d = -0.19$). Overall, very few mistakes were made. Out of the 330 participants, 218 (66%) made no mistakes at all, and 75 (23%) made a maximum of only one mistake per form. On average, the participants made 0.44 mistakes ($SD = 0.82$), with no significant difference between the male and female participants ($M_{male} = 0.47$, $SD = 0.83$ vs. $M_{female} = 0.39$, $SD = 0.81$; $t(328) = -0.90$, $p = 0.38$, Cohen's $d = -0.10$).

Correlation with age

In general, performance on the visuospatial memory task improved with age. Pearson's correlation showed that the participants' fraction of recall on the visuospatial memory test was positively correlated with their age (Pearson's $r = 0.37$, $p < 0.001$). On average, the fraction of recall increased by 0.015 points for every year increase in age (95% confidence interval [CI] = [0.011, 0.019]) (Figure 3A). The fraction of false alarms was negatively correlated with age (Pearson's $r = -0.36$, $p < 0.001$). A one-year increase in age resulted in a 0.014-point decrease in the fraction of false alarms (95% CI = [−0.018, −0.010]). The visuospatial memory span was positively correlated with age (Pearson's $r = 0.22$, $p < 0.001$) and increased by an average of 0.11 points per year of age (95% CI = [0.06, 0.16]) (Figure 3B).

The fraction of correctly reproduced sequences per sequence length was positively correlated with age for all sequence lengths (Table 2). Thus, for all sequence lengths, the performance of the older participants was significantly better than that of the younger ones. This difference with age was strongest for sequence lengths of four and five. The mean reproduction time per trial also decreased with age (Pearson's $r = 0.28$, $p < 0.001$), with a mean decrease of 0.19 s per year (95% CI = [−0.26, −0.12]. The average reproduction time per sequence length was significantly negatively correlated with age for all sequence lengths, indicating that for all sequence lengths, the participants' responses became faster with age (Table 2).

The DOT score was strongly positively correlated with age (Pearson's $r = 0.66$, $p < 0.001$) (Figure 3C).

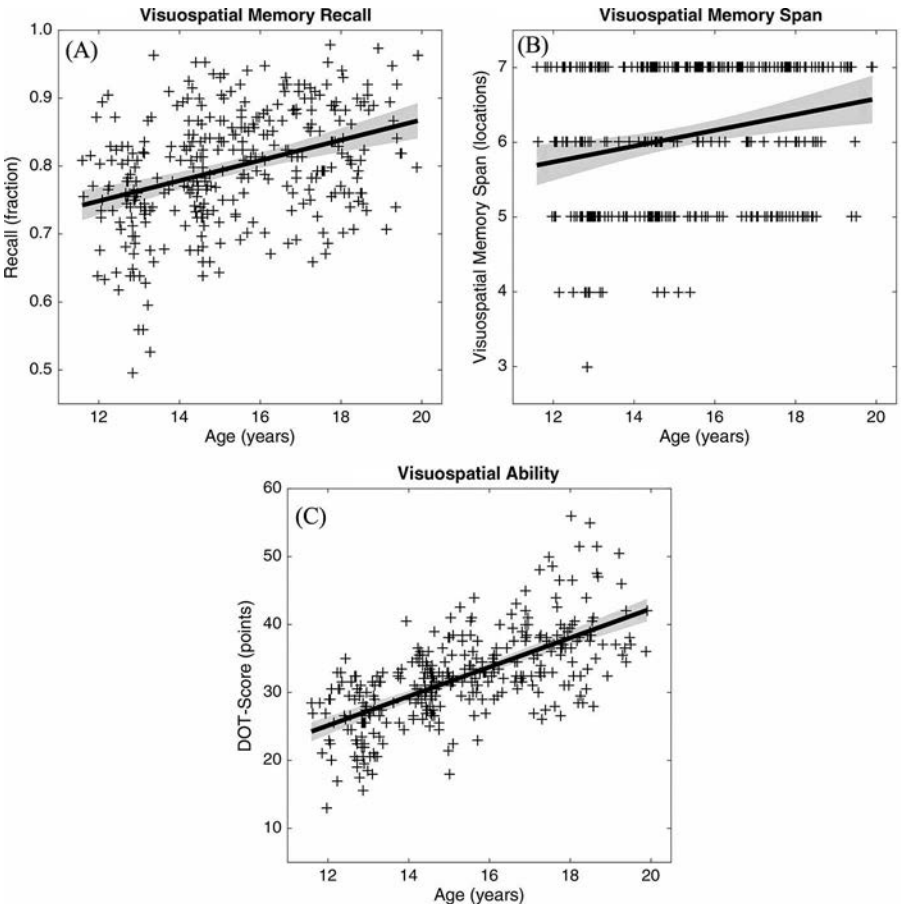

Figure 3. Performance throughout adolescence. Each point represents an individual participant. Gray areas depict 95% confidence intervals. A: Fraction of recall (i.e. the fraction of cued locations that were correctly reproduced). B: Visuospatial Memory Span. C: Score on the Design Organization Test.

On average, a one-year increase in age corresponded to a score increase of 2.1 points (95% CI = [1.9, 2.4]). The Pearson's correlation between age and the number of mistakes showed that these two variables were not significantly correlated (Pearson's $r = -0.03$, $p = 0.54$).

Partial correlation between tasks

Both visuospatial memory and visuospatial ability were assessed in the same population of 330 people, enabling assessment of the partial correlation between the outcome measures of both tasks, corrected for age.

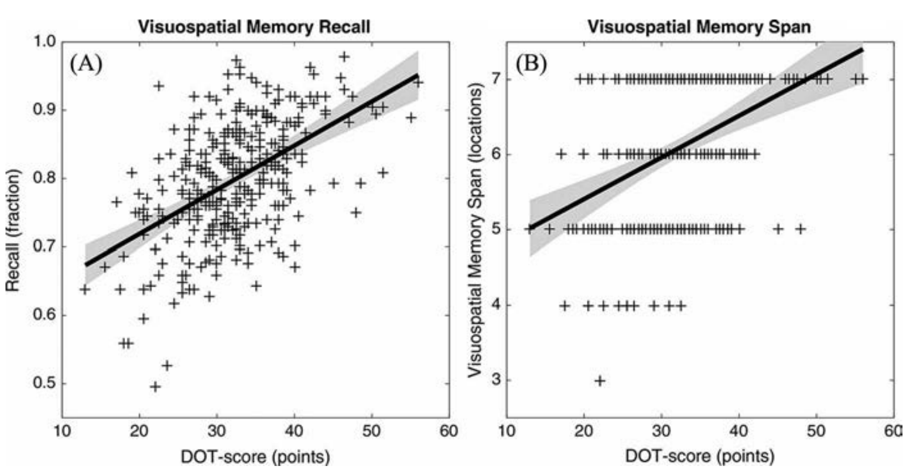

Figure 4. Performance on the visuospatial memory task versus the score on the Design Organization Test. Gray areas depict 95% confidence intervals. A: Fraction of recall. B: Visuospatial Memory Span.

This partial Pearson's correlation revealed significant correlations between the DOT score and the outcome measures for the visuospatial memory task, excluding the reproduction time.

We found strong and significant correlations between the DOT score and the fraction of recall (Pearson's $r = 0.39$, $p < 0.001$) (Figure 4A), the fraction of false alarms (Pearson's $r = -0.34$, $p < 0.001$) and the visuospatial memory span (Pearson's $r = 0.32$, $p < 0.001$) (Figure 4B). The DOT score and the fraction of correctly reproduced sequences were significantly correlated for all sequence lengths (Pearson's r varying between 0.13 and 0.37; all $p < 0.02$). In contrast, the partial correlation between the DOT score and the overall average reproduction time failed to reach significance (Pearson's $r = -0.08$, $p = 0.14$).

Discussion and conclusions

In the present study, a very large sample of 330 adolescents (11–20 years, one school, homogeneous socio-economic background), participated in two visuospatial tasks in a cross-sectional design. The results showed that performance on visuospatial memory and visuospatial ability tasks increase with age up to late adolescence, with no gender difference. Additionally, performance on the visuospatial memory and the visuospatial ability tasks showed a significant correlation. In particular, in the visuospatial memory task, the fraction of correctly reproduced locations, as well as the participants' visuospatial memory span increased with age. Additionally, for each sequence length, the older adolescents were able to correctly reproduce a sequence of locations more often than the younger adolescents. Furthermore, both the number of errors and the time needed to reproduce a sequence decreased with age.

The results of the memory task employed in the present study showed that performance improved until late adolescence. Development of performance on nonverbal working memory tasks has been shown to vary with varying levels of executive demands (Conklin et al., 2007). For instance, recognition memory reaches an adult level before the age of nine, the ability to maintain and manipulate multiple items develops until approximately 14 years of age, and strategic self-organization in memory tasks increases until 17 years of age (Luciana, Conklin, Hooper, & Yarger, 2005). In the Corsi block-tapping task, which inspired our task, the span capacity has been found to reach an adult level of performance during the early phase of adolescence, at approximately 14 years of age (Luciana & Nelson, 2002; Pagulayan, Busch, Medina, Bartok, & Krikorian, 2006). In our visuospatial memory task, we observed that performance increased until late adolescence, which might be related to differences in the temporal aspects of the Corsi task and the task used in this study. As in the Corsi block-tapping task, the presentation of the cued locations in our task was sequential. However, participants were not required to remember the order of the cued locations. Nonetheless, not requiring memorizing the temporal order might evoke a process of finding any kind of spatial order in the cued locations in order to support memorization. This spatial organization process must be updated each time a new location is cued. This type of self-ordered task places a greater demand upon executive attentional processes (updating, inhibition) and thus matures later in the adolescence period than the less demanding Corsi block-tapping task, which potentially explains the continuing increase in performance until early adulthood, observed in our task.

Although no instruction was given to respond as quickly as possible, we observed a decrease in the average reproduction time for each of the five different sequence lengths. This finding is in line with the increased processing speed of cognitive information with age that has been reported for many other cognitive tasks (Kail, 1991a, 1991b). This suggests that reproduction time in memory tasks may be an interesting parameter to evaluate when assessing visuospatial memory during adolescence.

The measure of false alarms for individual locations in the reproduction of a memory task is a measure that has not received much attention. Literature on visuospatial working memory traditionally focuses on measures of correct or incorrect recalls of complete sequences (Cornoldi & Mammarella, 2006). However, a few studies, have analyzed several types of errors: intrusion errors (reproducing locations that were cued but had to be ignored during reproduction; Lecerf & Roulin, 2009; Mammarella & Cornoldi, 2005), invention errors (reproducing locations that were not cued; Mammarella & Cornoldi, 2005), and spatial errors (cued locations that were not reproduced; Lecerf & Roulin, 2009). The analysis of error type and number might provide insight into the strategy used by a participant. For instance, one might play it safe and only select the locations of which he/she is sure, or one might select many locations in the hope that at least some of them were cued. This might specifically be important to report when studying adolescents because the ability to use strategies continues to develop during adolescence (Diamond, 2015). We found that the number of false alarms (called "invention errors" by Cornoldi and Mammarella (2006)) significantly decreased with age, making the scoring of errors in visuospatial working memory tasks an interesting supplemental measure to report in assessing the development of visuospatial memory during adolescence.

In our visuospatial ability task, a one-minute version of the DOT, the scores increased with age while the number of mistakes did not change significantly. These observations are highly consistent with previous findings in a smaller group of 198 adolescents (Burggraaf et al., 2015). The current independent replication of the results of that earlier study confirms the previous finding that the one-minute version of the DOT is an effective tool for measuring visuospatial abilities in adolescents. The increase in score with age is also in line with the findings of earlier studies that measured similar visuospatial abilities using a visual matching task (Kail & Ferrer, 2007) and the Block Design task (Shah & Frith, 1993), a sub-test of the Wechsler Adult Intelligence Scale (Groth-Marnat & Teal, 2000).

Performance on the two tasks was highly correlated. This is in good agreement with previous findings of the performance of a group of 167 university students using the Corsi block-tapping task and the Hidden Patterns task (Miyake et al., 2001). Importantly, the correlation found in our study is not inflated by the attentional control associated with the sequence ordering in the Corsi task protocol as used by Miyake et al. (2001). Still, some measure of attentional control might have been necessary in our task to update the visual representation of the cued locations with the appearance each new location. Although the precise processes in the memory task that correlate with the DOT task remain undetermined, this attentional control may account for the relationship with the performance on the DOT task.

It should be noted that the current participants as well as the participants in the study of Miyake et al. (2001) were part of a healthy population. In healthy populations, spatial memory test performance is greatly enhanced by the ability to recognize patterns in some or all of the locations (van Hagen et al., 2007). This ability to recognize patterns is compromised in, for instance, patients diagnosed with Down syndrome (Lanfranchi, Mammarella, & Carretti, 2015) or Williams syndrome (Carretti et al., 2015; van Hagen et al., 2007), resulting in a much smaller increase in performance when cued locations are ordered instead of randomly distributed (Carretti et al, 2013). Interestingly, the difference in performance between ordered and random locations, both in typically and atypically developing children, is mainly discernable when all locations are presented at once (spatial-simultaneous tasks), not when the task is spatial-sequential (Carretti et al., 2013, 2015). This suggests that a spatial-sequential memory task, such as ours, places a higher demand on controlled attentional processes than does a spatial-simultaneous task, thus strengthening the correlation between our memory task and our visuospatial ability task. In a future study, it would be informative to assess whether the correlation observed here between these tasks is also present when the visuospatial memory task is converted into a spatial-simultaneous task with a lesser demand on attentional processing. This approach could shed further light on which process within the memory tasks is primarily responsible for the correlation between tasks found in this study.

No difference between male and female participants was observed in the results of either task. For the memory task, this result is consistent with the findings of Luciana et al. (2005). For the visuospatial ability task, the absence of a gender difference was consistent with the findings of Burggraaf et al. (2015) on the one-minute version of the DOT as well as the findings on the two-minute version of the DOT by Killgore (Killgore et al., 2005; Killgore & Gogel, 2014). Although an increasing time demand has been shown to increase the performance difference between the sexes in some tasks (Voyer, 2010), in general, sex differences between the sexes in the performance on visuospatial tasks are small, if present at all, and occur primarily in tasks concerning mental rotation (Linn & Petersen, 1985; Luciana et al., 2005). The absence of mental rotation in the DOT may explain this equal performance of the two sexes.

Our memory task was inspired by the Corsi block-tapping task (Corsi, 1972) but differed from it in three ways. First, we increased the number of possible locations to 36; the Corsi task uses only nine. This change was made to present many different sequences of the same length without repeating locations. Second, our memory test did not require the participant to memorize and reproduce the sequence of locations in the same order in which it was presented, as is required in the Corsi block-tapping task. A pilot study showed that correctly reproducing the locations in the same temporal order with this many possible locations became extremely difficult, critically decreasing the motivation of the participants and inducing considerable inter-trial variability. Advantageously, this change at least partially removes one source of attentional control in task performance, resulting in a calculated visuospatial measure that is less influenced by the sequential aspect of the task. Of course, this temporal aspect of memory and its potential influence on the correlation with other visuospatial abilities might also be an interesting factor in cognitive development during adolescence; however, in our view, this idea deserves a separate study. The third difference between our memory task and the Corsi block-tapping task is the method of administration. The Corsi task is administered in a one-on-one setting between an administrator and participant, using blocks specifically made for this task, while our task was made to run on any computer able to run Java scripts, which are widely used. This computerization of the memory tasks facilitates a less labor-intensive administration of the task (Cornoldi & Mammarella, 2008; Rowe et al., 2009; Vandierendonck et al., 2004). This different form of task administration has been shown to result in memory spans and error rates that are similar to the physical administration of the Corsi block-tapping task (Brunetti et al., 2014) as well as for a variation of this task (Kessels et al., 2002).

The differences from the Corsi block-tapping task resulted in several advantages. First, due to the use of a computer program, our task can be administered simultaneously to a large group instead of only in a one-on-one setting. Second, because of the use of a computer program, for each individual participant of the group the time needed to reproduce each sequence of location was automatically registered for each individual participant of the group, which would otherwise only have been possible in a one-on-one setting. Because we did not instruct the participants to respond as quickly as possible, we cannot make firm claims, but we did observe a decrease in reproduction time with age and not with performance on the visuospatial ability task. For this reason, reproduction time might be an interesting measure of visuospatial memory performance to evaluate in adolescence research. Last, while in the Corsi task the sequences are only presented once or twice and upon making a mistake, the participant is not allowed to try the longer sequences, in our memory task, all sequence lengths are presented multiple times and all participants are presented with all 36 trials. This method of administering the task has been used before (Giofrè et al., 2013; Hornung et al., 2011) and enables a more detailed estimate of the memory performance than measuring the span level reached. This estimate was obtained by determining the fraction of recall, which was the fraction of correctly reproduced cued locations. This fraction of recall correlated strongly with the visuospatial memory span of the Corsi task but the fraction of recall can range from 0 to 1 in steps of 0.0053, while the outcome of the memory span is limited to 3, 4, 5, 6, or 7. This makes the fraction of recall more sensitive to individual differences, and it showed a stronger correlation with age. This might be important, for instance, in a longitudinal experimental setup, where differences in memory performance while growing up might be small.

Our study employed a cross-sectional design, whereas a longitudinal approach would allow the assessment of the development of visuospatial memory and ability in individuals and possibly allow for the correction of inter-subject variation in, for instance, general intelligence. As a next step, we are setting up a longitudinal design by taking advantage of the convenient fact that our participants will attend the same school for six years. However, only students with high scores on a national intelligence test attend this school, hampering the generalization of our findings to children of different backgrounds and education levels. Therefore, it would be ideal to conduct similar tests at other schools, which could be difficult because it is not always possible to find large groups of adolescents who are willing to participate voluntarily.

Visuospatial abilities and memory performance are important parts of the cognitive development that occurs during adolescence, both at school and in life in general. The results of the tasks used in this study, both individually and in combination, provide insight into these aspects of the cognitive capacities of adolescents. Our results show an increase in performance in both visuospatial memory and abilities during the whole period of adolescence up to early adulthood. We also found a significant correlation between performances on both tasks. Our findings suggest that also during adolescence, both visuospatial memory and abilities tap into the same resources and that the increase in performance in both tasks results from the continuous maturation of the executive functioning of the child. Finally, the variation of the Corsi block-tapping task used in this study provides a more sensitive measure of the visuospatial memory capacity than the conventional memory span of the Corsi task. This enables the assessment of small differences that might occur during adolescence. We also found that two very infrequently reported measures, response time and proportion of false alarms, are correlated with age during adolescence. These measures can easily be included in assessments, providing extra detail in assessing a child's memory performance and development. Finally, the combination of a visuospatial memory task with a visuospatial ability task provides deeper insight into which of the processes involved in memory performance are responsible for increased performance during maturation. The annual tracking of an adolescent's visuospatial memory and visuospatial ability performance and their correlation can support the often-difficult choices students and their parents, teachers and mentors have to make as a student proceeds through the educational system. Thus, such an analysis would be a valuable tool for guiding students on their path to adulthood.

Acknowledgments

Thanks to Vincent Bolta for quickly and accurately programming the visuospatial memory task as a stand-alone application and thereby facilitating the running of the experiment with large groups of participants. Thanks to the students, teachers and (con)rector of the Gemeentelijk Gymnasium Hilversum for facilitating access to the time and labspace needed to run this experiment and to Stefan Meijlink for his help with collecting the large amount of data for this study.

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