Development of Visual Search Behavior during Adolescence

Rudolf Burggraaf

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Cover: picture of the experimental set-up with the autographs of all the children who participated in the longitudinal experiment.

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Ontwikkeling van visueel zoekgedrag tijdens de adolescentie

Proefschrift

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Erasmus Universiteit Rotterdam
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Contents

1. General introduction

Years ago I was teaching mathematics to a secondary school student. One moment he was behaving dependable and rational and studying hard for his exams. Then, suddenly between exams, he threw all caution in the wind and headed of to Paris with a friend 'because they felt like it', neither telling teachers nor parents. Many a teacher and parent have been pushed to a near-madness state because of the unpredictable behavior of adolescents. Ever since the 15th century (D. Beekman, 1977) writers of many books have been trying to provide adults with tips and tricks to navigate the precarious waves of hormones in adolescents. Experience of family members and elders of a group mainly formed the basis of these guidelines. Later, results from behavioral and psychological research were added to these guides. In the last decennia though, explanatory books for parents have been written that combine all these sources with insights obtained by neuroscience. A well-known example is the book 'Het puberende brein' (English translation: the adolescent brain; prof. dr. Eveline Crone). Books like these try to provide parents with a different, neuroscientific, view on the development of their child. Though this does nothing to change the behavior of the child, it helps parents to understand what is happening, and thereby make it easier to accept and celebrate the difficult and wonderful phase of adolescence. In this thesis we provide yet another view on changes during adolescence, specifically by studying the eye movements of a group of adolescents while growing up. We describe how these eye movements change with age and also investigate if visual skills like pattern recognition and location memory affect eye movements.

While growing up from infancy to young adulthood, children's behaviors change while they develop and improve many different abilities such as social cognition, organization, decision making and planning (Crone 2008; Blakemore, 2008; Spear, 2000; Yurgelun-Todd, 2007). An adult-like performance level is achieved at different points in development for different cognitive tasks (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, 1991). With the use of neuroimaging techniques it has become clear that different periods of development of skills correlate with the different maturational timing of different brain regions (Casey, Tottenham, Liston, & Durston, 2005). For instance, skills associated with top-down behavioral control and performing goal-oriented tasks depend heavily on the functioning of the (pre-) frontal cortex, an area that still matures during adolescence (Crone, 2008). Therefore, during adolescence children improve their ability to control their thoughts and actions to make them consistent with internal goals. These executive functions are thought to be central to human cognition and individual differences among children in brain maturation have been shown to be closely related to differences in intellectual functioning (Koenis et al., 2015). Together with the pre-frontal cortex though, executive functions are not fully matured until late adolescence or perhaps not even until early adulthood (Crone, 2009). Therefore adolescence can be seen as a period of significant cognitive advancements in which the efficiency of many skills and activities increases.

Most activities share the need to visually search for information and/or objects before acting upon them (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Land, 2006). This has, for instance, been studied while making a cup of tea (Land et. al, 1999) or making a peanut butter and jelly sandwich and pouring a glass of water (Hayhoe et. al., 2003). Participants did this while wearing an eye-tracker mounted on the head so their eye movements could be studied while performing these activities. The necessary items were laid out on the table in front of the observer with a number of arbitrarily chosen irrelevant items (other food items, tools, silverware) interspersed with the items required for the task. On the initial exposure of the scene, participants scanned the scene and made a series of fixations on the objects, before the first reaching movement was initiated. After that, each physical action was preceded by a visual search for the required object (Land, 2006). While the action was in the course of being performed, the visual search for the next object already started. Similar behavior has also been shown in very different examples of activities like in driving a car (Land & Lee, 1994) and playing sports like cricket (Land & McLeod, 2000) and table tennis (Land & Furneaux, 1997). Because visual search forms such an intricate part of so many daily activities, changes in visual search might tell us a lot about the changes in behavior we see during adolescence.

In this thesis we study how visual search performance and behavior changes while growing up as an adolescent (Chapter 4). We also investigate if these changes are also affected by changes in other visual skills like spatial memory and pattern reconstruction (Chapter 5). In this introduction we provide a brief description of the different possibilities to investigate individual performance on these types of tasks.

A visual search task could be set up in many different ways, each with their own daily-life analogy. The task can, for instance, vary between ‘search until you find the target' and 'decide whether the target is present or not'. The display in which the participant has to search for the target can vary in, for instance, the number of targets, the number of other elements than the target that are present in the display and in the extend that the other elements share visual characteristics with the target.

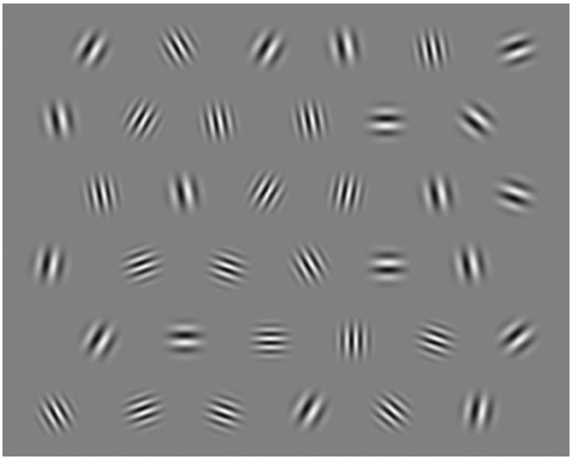

Figure 1.1 – An example of the search pictures used in our experiments where one doesn't know beforehand whether the target is present or not. The elements are depicted four-times enlarged for visibility purpose. The target was always an element with high-spatial frequency of which the lines were vertically oriented.

In our research we used a visual search task where the target that the participant had to search for was present in 50% of the pictures (Figure 1.1; chapter 4 and 5). He or she was asked to decide as quickly and as accurately as possible whether the target was present or absent. In these kinds of visual search tasks, two aspects are regularly assessed: performance and behavior. Search performance relates to the result of the search: how fast and how accurate is the response. Search behavior describes the way the search is executed. During search, fixations are interleaved with rapid eye movements, called saccades (Kowler, 2011). During a fixation observers analyze the fixated object, select the most interesting object to fixate on next and plan the corresponding eye movement (Irwin, 2004; Findlay, 1997; Hooge & Erkelens, 1999; Luria & Strauss, 1975; Zelinsky, 2008). Thus search behavior could be described by, for instance, the location, the duration and the number of fixations that were made during the search.

Previous publications show that visual search performance and behavior differ between children, adolescents, and adults (Plude, Enns, & Brodeur, 1994). Children between 9 and 15 years of age search faster as their age increases

(Seassau & Bucci, 2013). In contrast, adults between 25 and 70 years of age search slower as they become older (Hoyer, Cerella, & Buchler, 2011; Trick & Enns, 1998). These findings suggest that search performance peaks sometime between 15 and 25 years of age. This suggestion is supported by a study that involved groups of participants who were between 6 and 88 years old (Hommel, Li, & Li, 2004). In this study, late adolescents (15-22 years old) and young adults (23-33 years old) performed faster than the younger and older age groups. The acceleration of visual search is largely a result of shorter fixation durations while the number of fixations does not change significantly with age (Huurneman & Boonstra, 2015; Seassau & Bucci, 2013). In contrast to reaction time, response accuracy shows no significant difference among age groups (Huurneman & Boonstra, 2015; Trick & Enns, 1998).These studies compared the average search performance and search behavior of groups of participants in broad age ranges, therefore losing information regarding the changes in the individual performances.

All aforementioned, cross-sectional, studies correlate differences in visual search to changes in age, but do not take into account that age-related changes in other visually related abilities, such as visuospatial abilities and visuospatial memory, might mediate these changes. Visuospatial abilities, for instance, include part-to-whole integration and pattern recognition (Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Linn & Petersen, 1985). One might hypothesize therefore that better visuospatial abilities might make it more feasible to systematically scan the search display and increase the change to find the target. Also one might hypothesize that a better visuospatial memory might help to keep the overall layout of the display in mind while fixating the individual elements. This could make the choice of elements to fixate next more efficient.

Previous publications show that both visuospatial memory and visuospatial ability depend heavily on executive functioning and are strongly correlated (Miyake et al., 2001), Executive functioning continues to mature during adolescence up to early adulthood (Giedd et al., 1999). Earlier studies have shown that visuospatial ability and visuospatial memory increase with age during childhood (Eisner, 1972; Kohs, 1920; Shah & Frith, 1993; Alloway, Gathercole, & Pickering, 2006; Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Cestari, Lucidi, Pieroni, & Rossi-Arnaud, 2007). Studies into the correlation between visuospatial ability and visuospatial memory, though, have focused solely on adult populations (Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001) and small children (Giofrè, Mammarella, & Cornoldi, 2013). A description for the full adolescence period has, to our knowledge, not been published. Based upon the combined findings above, we hypothesize that also during adolescence changes in visual search, visuospatial memory and visuospatial ability are correlated and correlated with age.

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 (WAIS-III) (Wechsler, 1981; Groth-Marnat & Teal, 2000). This test reveals improvement in adolescents' visuospatial abilities with age (Kohs, 1920; Shah & Frith, 1993) while in adults they are negatively affected by age (Killgore et al., 2005). Unfortunately, the use of the Block Design test does have certain drawbacks such as the need for specific materials, requiring prolonged periods of focus and the administration on an individual basis, requiring both time and resources.

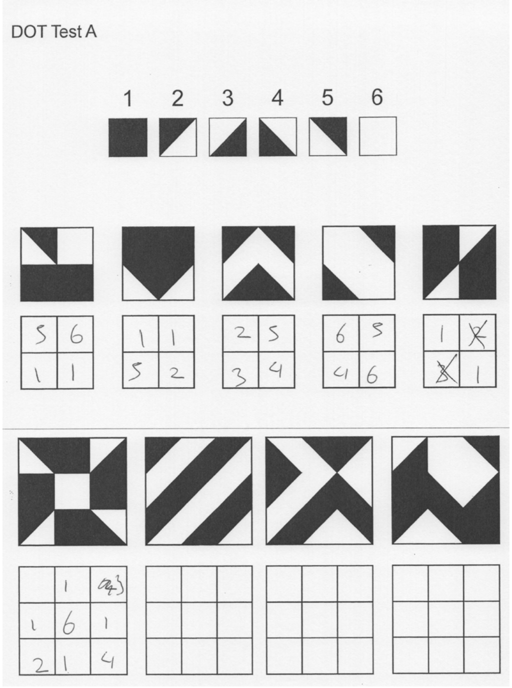

Figure 1.2 – An example of one of the versions of the Design Organization Test (DOT) in which the figures had to be reproduced using a numerical code that was provided at the top of the page. This participant scored 32 correct squares and made two mistakes.

To measure the visuospatial ability of participants we used the Design Organization Test (DOT; Killgore et al., 2005; Figure 1.2; chapter 2 and 3). This is a brief paper-and-pencil version of the Block Design Test, which is a subtest of the Wechsler Adult Intelligence Scale-Third Edition (Groth-Marnat & Teal, 2000). The results of the DOT have been shown to correlate strongly with the results of the Block Design Test in healthy adults (Killgore & Gogel, 2014) and neurological patients (Killgore et al., 2005) but not yet in adolescents. We used a slightly shortened version of the DOT to measure visuospatial ability in adolescents. The shortening of the administration time from two to one minute was necessary to avoid a ceiling effect in the score that had become clear in a pilot experiment. In order to determine if the DOT is a viable option for measuring the visuospatial ability of adolescents, we compared our results with findings of other studies using similar populations but different tests like the Block Design Test. We also investigated if it would be possible to assess the visuospatial ability of a large group of students at once, for instance in a classroom, administering the DOT group wise. Therefore we compared the correlation between age and DOT score in the two different situations (Chapter 2).

A much-used test to measure visuospatial memory is the Corsi block-tapping task (Corsi, 1972). In the Corsi block-tapping task several blocks are laid down on a table in front of the participant and participants are required to memorize a varying number of locations that are demonstrated by the experimenter. This way, visuospatial memory has often been studied in younger children (Alloway, Gathercole, & Pickering, 2006; Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Cestari, Lucidi, Pieroni, & Rossi-Arnaud, 2007) showing an increase in memory capacity. Findings in groups of adolescents also revealed an improvement in performance on memory tasks but unfortunately the results were collapsed and averaged over various age ranges (Conklin, Luciana, Hooper, & Yarger, 2007; Gathercole, Pickering, Ambridge, & Wearing, 2004; Luciana & Nelson, 2002; Rowe, Hasher, & Turcotte, 2009; van Leijenhorst, Crone, & Van der Molen, 2007) making it impossible to properly quantify the relationship between visuospatial memory performance with age.

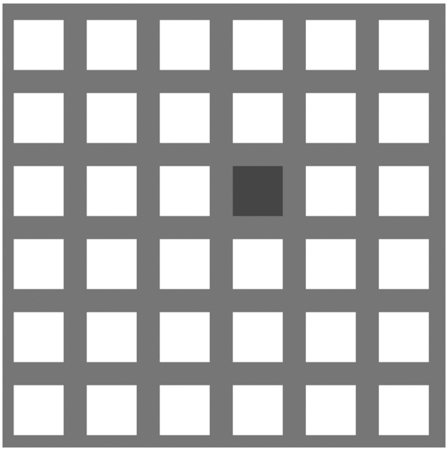

Figure 1.3 – Our computerized version of a visuospatial memory task. On a regular grid of 36 locations a sequence of 2 up to 7 blocks lit up sequentially. After a break of a few seconds the participant had to reproduce this sequence using the mouse or track pad of the computer.

We designed a computerized task that was loosely based on the Corsi Block-tapping task (Figure 1.3, Chapter 3). One of the advantages of a computerized task is that it makes group wise administration possible, greatly reducing the time needed to administer the task to a classroom full of students. Computerized versions 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 task (Brunetti, Del Gatto, & Delogu, 2014). The measures often used for memory capacity are usually rather coarse. In order to make our task sensitive to the small, individual differences in performance among children of a similar age, we increased the number of trials, providing a possibility for a finer scale of memory span measurements.

The general aim of the present thesis is to investigate the development of visual search across adolescence and correlations with other visuospatial characteristics like visuospatial ability and visuospatial memory. First we studied, in a cross-sectional design, whether visuospatial ability is different for older children compared to younger children. In the course of this study we investigated the possible use of the Design Organization Test (DOT) for the adolescence age group, and also the possibility to use the DOT to asses the visuospatial skill within a group settings instead of an individual settings (Chapter 2). Secondly, we examined the difference in visuospatial memory for children of different age during adolescence and the correlation between visuospatial memory and visuospatial ability as measured with the DOT (Chapter 3). Our last cross-sectional research was aimed at describing the differences in visual search performance and visual search behavior between adolescents of different age. In this study we also extensively investigated the way visual search behavior is affected by characteristics of the fixated elements like spatial frequency and orientation (Chapter 4).

The developments of visuospatial ability and visuospatial memory with age, however, vary between subjects. This hampers the proper assessment of the relationships between age, visuospatial skills and visual search in a cross-sectional design. Therefore we performed a longitudinal study among the children that participated in the cross-sectional studies. This study consisted of four identical measurements with one-year intervals. During each measurement, the same tasks were used as in the cross-sectional studies (Chapter 5). This thesis ends (Chapter 6) with a general discussion of the results of all studies together as well as some suggestions for further research.

2. A quick assessment of visuospatial abilities in adolescents using the Design Organization Test

Published

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Abstract

Tests measuring visuospatial abilities have shown that these abilities increase during adolescence. Unfortunately, the Block Design test and other such tests, are complicated and time-consuming to administer, making them unsuitable for use with large groups of restless adolescents. The results of the Design Organization Test (DOT), a quick pen-and-paper test, have been shown to correlate with those of the Block Design test.

A group of 198 healthy adolescents (110 males and 88 females) between the ages of 12 and 19 years participated in this study. A slightly modified version of the DOT has been used in which we shortened the administration time to avoid a ceiling effect in the score.

Scores show a linear increase with age (on average 2.0 points per year, $r = .61$), independent of sex. Scores did not differ between individual or group setting. Thus, the DOT is a simple and effective way to assess visuospatial ability in large groups, such as in schools, and it can be easily administered year after year to follow the development of students.

Keywords: visuospatial ability, adolescence, age, Design Organization Test (DOT), Block Design test

Introduction

During adolescence parts of the brain are still developing, resulting in the improvement of several abilities, including visuospatial abilities (Eisner, 1972; Shah & Frith, 1993). Visuospatial abilities are often measured using standardized tests, and performance on these tests is occasionally used as a proxy for intelligence (Hurks, 2013). One such standardized test is the widely used Block Design test, which is a subtest of the Wechsler Scale of Intelligence (WAIS-III) (Groth-Marnat & Teal, 2000). This test reveals improvement in adolescents' visuospatial abilities with age (Kohs, 1920; Shah & Frith, 1993).

Unfortunately, the use of the Block Design test does have certain drawbacks. For example, it requires specific materials (blocks with patterns) that are not readily available to every research group. In addition, the test must be administered on an individual basis, requiring both time and resources. It can also be challenging to test participants due to its lengthy nature; a complete examination may take more than 20 minutes. The test length may pose particular problems for adolescents, as they often have limited attention spans and low motivation to participate. These issues limit the use of the Block Design test as an instrument to evaluate the development of visuospatial abilities in adolescents.

To rapidly assess visuospatial abilities, Killgore and colleagues developed the Design Organization Test (DOT) (Killgore et al., 2005). This brief paper-and-pencil test consists of square black-and-white grids with patterns similar to those of the Block Design test. Within two minutes, test participants reproduce as many patterns as possible using a numerical code key. Scoring is conducted by simply counting the number of fields in the grids that have been filled in correctly. The DOT is simple and straightforward to administer and easy to evaluate, and it can therefore be used in situations with limited assessment time. Killgore (2005, 2014) showed that the results of the DOT significantly correlate with those of the Block Design test, thus making the DOT a reliable alternative. This idea is supported by findings from 61 healthy adults between 18 and 45 years of age (Killgore & Gogel, 2014) and from a group of 41 neurological patients (18–76 years old) (Killgore et al., 2005).

In adults, visuospatial abilities as measured by the DOT are negatively affected by age (Killgore et al., 2005) and positively affected by education (Killgore & Gogel, 2014). Although sex differences in some visuospatial tests have been reported (Kaufman, 2007; D. Voyer, Voyer, & Bryden, 1995), such differences only seem to apply to tasks that involve mental rotations (Linn & Petersen, 1985). This cognitive process is not required in the DOT, which explains why sex differences have not been found in the DOT results (Killgore & Gogel, 2014).

The aim of the present cross-sectional study was to evaluate the development of visuospatial abilities in a large group of healthy adolescents between 12 and 19 of age by using a slightly modified version of the DOT in which we shortened the administration time to avoid a ceiling effect in the score. We expected that performance on the DOT during adolescence would increase with age and be independent of sex, indicating an improvement in visuospatial abilities.

Methods

Participants

A total of 198 pupils (110 males, 55.6%) participated in the study, and their ages ranged from 12.3 to 19.1 years ($M = 15.0$ years, $SD = 1.8$). Participants were Caucasian adolescents recruited from all six grades of a secondary school in Hilversum, The Netherlands. Admittance to this school is reserved for students scoring in the highest 20% of a national educational achievement test score, CITO-test, which is taken at the end of primary school. The students who participated in this experiment followed the same broad educational program during the first three grades. In the last three grades, the focus of their curriculum was mainly on science and languages (including Latin and ancient Greek). The experiments were conducted during school hours. Participation was voluntary, and no incentives were provided. The study adhered to the Declaration of Helsinki, and participants signed an informed consent document.

Participants performed the test either individually (*N*= 66, 33%) or in a classroom setting (*N*= 132, 67%). In the classroom setting, between 15 and 25 participants performed the test simultaneously. Complete silence was maintained during the test.

Material

This study used the DOT developed by Killgore and colleagues (2005), which consists of two pages, labeled 'form A' and 'form B' (Figure 2.1).

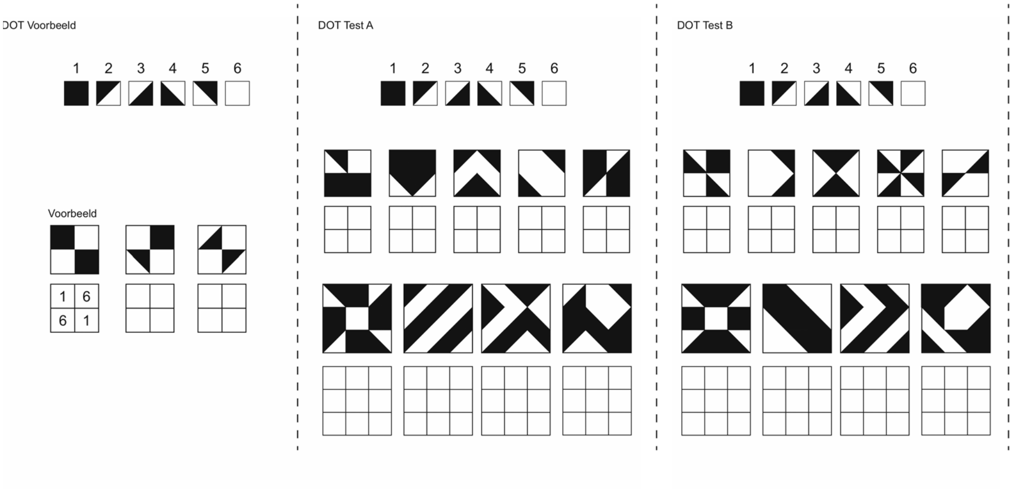

Figure 2.1 – The two forms, A and B, that were used for the Design Organization Test (DOT), along with the sample page. 'Voorbeeld' is Dutch for 'example'.

At the top of the page, a row of six squares is printed with a numerical key code from 1 to 6. Below that, there is a row of five 2x2 grids and a row of four 3x3 grids. Each grid shows a design or pattern that is composed of a specific combination of the squares above. Below each pattern, a grid with empty squares is printed; the participant fills in the empty grid with the numerical key codes that correspond to the design above. Form A and form B are very similar. The test also provides a practice form with the same six response key figures and three 2x2 practice blocks, one of which is already fully completed as an example (Figure 2.1).

Procedure

Before starting the experiment, the procedure was fully explained to the participants using the same text used in the studies of Killgore (Killgore et al., 2005; Killgore & Gogel, 2014), albeit in Dutch. Each participant first completed the practice form without any time constraints. The administrator then checked the responses to ensure that the participants correctly understood the instructions.

At a go-signal given by the administrator, each participant uncovered form A and was given 1 minute to fill as many empty squares as possible. After 1 minute, the participant was required to put down the pen and put form A aside. After a break of approximately 1 minute, the process was repeated with form B. We did not counterbalance the order of the two forms as previous findings (Killgore et al., 2005) showed both forms to be equally difficult.

The procedure used by Killgore (Killgore et al., 2005) (Killgore & Gogel, 2014) allowed the participants 2 minutes per form. In a study with first-year university students (Killgore et al., 2005), this timing resulted in approximately 10% of the participants reaching the maximum score. The pupils attending the higher grades in the present study have a comparable educational level; because a ceiling effect could negatively affect the possible correlation between age and score, a pilot study including 40 subjects was performed. The results showed that 13 of these subjects were indeed able to complete a form well within the time limit of 2 minutes. Therefore, we decided to shorten the time to 1 minute per form.

Analyses

For each participant, the total number of correct answers and mistakes was counted separately on each form. The Score (points) was defined as the number of squares filled in with the correct key code. The Number of Mistakes was defined as the number of squares filled in with an incorrect key code. Squares that were not filled in were not taken into account. For each participant, both the Score and Number of Mistakes were averaged over the two forms. Differences between male and female participants in the Score and Number of Mistakes were statistically assessed using Student's t-tests. Associations between age and Score and between age and Number of Mistakes were assessed using Pearson correlation. An association between level of education and Score was assessed using an ANOVA with one between-subject 'grade' factor with 6 levels (grade I-VI).

Results

All 198 adolescents participated as instructed in the 1-minute version of the DOT. The overall average score was 30.5 points (*SD* = 6.1), ranging between 16 and 53 points (Figure 2.2). As expected, the score of male participants (*M* = 30.3 points, *SD* = 5.9) did not differ from the score of female participants (*M* = 30.8 points, *SD* = 6.3, $t = -0.56$, $p = 0.58$).

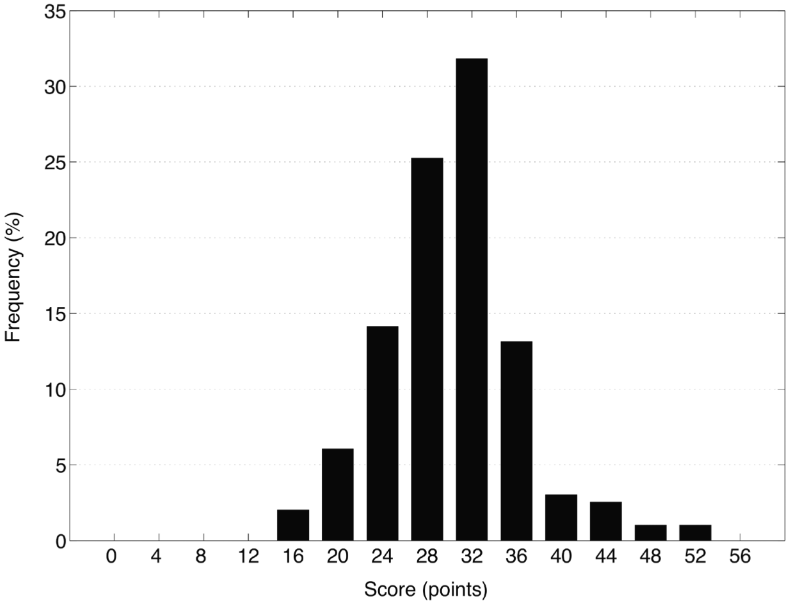

Figure 2.2 – Distribution of the DOT scores of 198 adolescent participants. The scores were binned at 4-point intervals.

A total of 12,309 squares were filled in with only 1.1% being incorrect. On average, each participant made 0.60 mistakes (*SD* = 1.1). Among the participants, 111 made no mistakes at all, 73 made one or two mistakes, and 14 made three or more mistakes. In most of the latter cases, the mistakes consisted of an interchange between the two numbers corresponding to the black and white squares. There was no significant difference in the Number of Mistakes between male (*M* = 0.66, *SD* = 1.1) and female participants (*M* = 0.53, *SD* = 1.1; $t = 0.86$, $p = 0.61$).

Ceiling Effect

A pilot study had shown that many of the pupils who attend this high-level secondary school were able to reach the maximum score well within 2 minutes. To avoid this ceiling effect, we reduced the time allowed per form from 2 minutes to 1 minute. This modification resulted in none of the participants reaching the maximum score of 56 points.

Age and Education

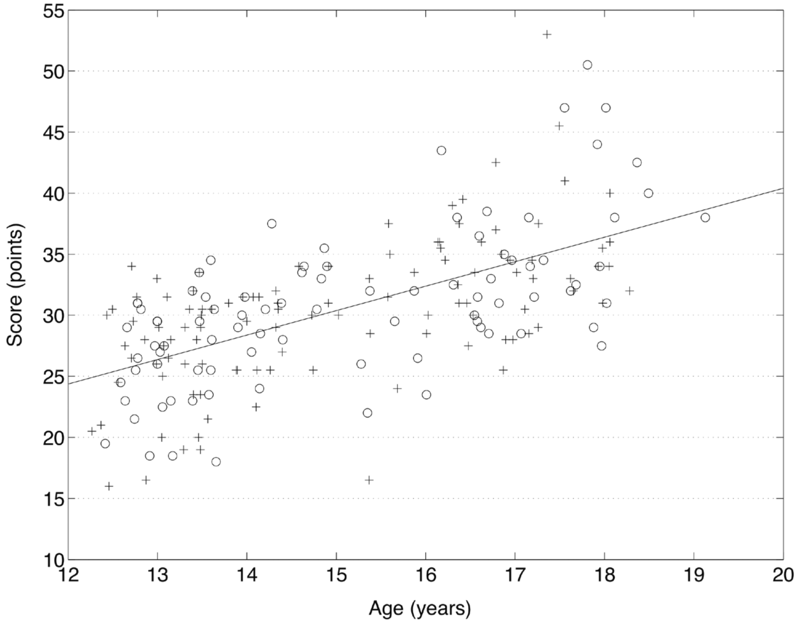

Figure 2.3 – DOT score versus age, separated according to the gender of the participant. Each point represents an individual subject. '+' denotes a male, whereas 'o' denotes a female.

The results showed a strong, positive correlation between score and age (Pearson $r = 0.61$, $p < 0.001$, Figure 2.3). A difference in age of one year resulted in an average difference of 2.0 points in the Score (95% confidence interval: 1.6 - 2.4 points). When we analyzed the two forms A and B separately, similar results were obtained; an increase of 2.0 points (95% confidence interval: 1.7 - 2.4 points, $r = 0.60$, $p < 0.001$) per year was observed for form A, and an increase of 2.0 points (95% confidence interval: 1.6 - 2.4, $r = 0.58$ $p < 0.001$) per year was observed for form B. The Number of Mistakes showed no correlation with age (Pearson $r = -0.07$; $p = 0.33$).

Table 2.1 – DOT score per grade; The number of participants (N), the age, and the DOT score for each of the six grades.

Grade	N	Age (years) mean (SD)	Score (points) mean (SD)
I	62	13.0 (0.4)	26.4 (4.7)
II	35	14.0 (0.4)	28.7 (3.7)
III	13	15.1 (0.3)	29.0 (5.8)
IV	25	15.9 (0.6)	32.6 (4.2)
V	37	16.9 (0.5)	33.6 (5.2)
VI	26	17.8 (0.3)	36.9 (6.1)

As expected, the Score also increased with grade ($F[5] = 23.2$, $p < 0.001$, $\eta^2 = 0.376$, Table 2.1). This result is not surprising given the very high correlation between age and grade (Pearson $r = 0.973$; $p < 0.001$).

Individual versus classroom setting

The experiment was administered in two different settings, either individually or in a classroom with approximately 20 participants. The Scores of the 66 participants who performed the test individually ($M = 29.5$ points, $SD = 4.9$) did not significantly differ from the Scores of the 132 participants who performed the test in a classroom setting ($M = 31.0$ points, $SD = 6.5$ points; $F[1] = 0.236$, $p = 0.63$, adjusted for age).

Practice Effects

In this experiment all participants were first presented with form A and then with form B. There was a strong correlation between the scores of forms A and B (Pearson $r = 0.80$, $p < 0.001$). Participants showed an individual improvement, scoring more points on form B ($M = 31.7$ points, $SD = 6.9$) than on form A ($M = 29.2$ points, $SD = 5.9$; $t = -8.397$ $p < 0.001$). This improvement differed neither with age (Pearson $r = 0.082$, $p = 0.248$) nor with score (Pearson $r = 0.04$, $p = 0.58$). The Number of Mistakes on form B ($M = 0.48$, $SD = 1.25$) was slightly lower than that on form A ($M = 0.72$, $SD = 1.52$), although this result was only marginally significant ($t = 1.95$, $p = 0.052$).

Discussion and Conclusions

The aim of the present cross-sectional study was to evaluate the development of visuospatial abilities during adolescence using the DOT. All participants were pupils of the same secondary school, and their ages ranged from 12 to 19 years.

As expected, we observed that visuospatial performance improved with age during adolescence. This finding is in accord with many other studies (Kail, 1991; Kail & Ferrer, 2007). For example, Shah et. al. (Shah & Frith, 1993) employed the Block Design test and showed that the same level of visuospatial accuracy was reached faster by adolescents approximately 16 years old than those approximately 11 years old. Eisner (1972) used 10 different tests with a total of 16 measures of visual perception. On 12 of the 16 measures, a group of 14- to 17-year-olds performed at a significantly higher level than a group of 10- to 14-year-olds. We also observed that form B yielded a significantly higher score than the first form. This difference is most likely due to a short-term learning effect, as both forms are equally difficult (Killgore et al., 2005; Killgore & Gogel, 2014). Furthermore, the score increase was independent of age, sex or education. Notably, the scores on the two forms were highly correlated indicating good test-retest reliability for the DOT.

Similar to the studies by Killgore, we observed no differences between the male and female participants in the results of the DOT (Killgore et al., 2005; Killgore & Gogel, 2014). In general, the effects of sex on visuospatial ability have been shown to be small, if present at all (Weiss, Kemmler, Deisenhammer, Fleischhacker, & Delazer, 2003); these effects only appear in tasks that require mental rotation (Linn & Petersen, 1985). The absence of mental rotation in the DOT could explain the equal performance of both sexes.

In the present study, we tested participants either individually or in a classroom setting. We observed no differences between these two subgroups. This finding suggests that the DOT is an adequate instrument for the simultaneous assessment of the visuospatial abilities of large groups of participants. This feature of the DOT, in addition to the short time required to complete the test, gives the DOT major advantages over, for example, the Block Design test, which must be administered individually and can take more than 20 minutes to complete. These advantages make the DOT a suitable screening instrument for large-cohort studies. (Hofman et al., 2011; Koppelmans et al., 2012)

A minor disadvantage of the classroom setting is the inability to observe different strategies for filling in the forms and thus determining their effects on the score. In this study, when the DOT was administered individually, we discovered that most participants filled in the form one grid at a time; however, a few participants started filling in all squares belonging to one key code before moving to the next key code, and others drew additional lines in the patterns. However, a recent study by Killgore and Gogel (2014) assessing this issue showed no effects of strategy on performance in the DOT.

In a study by Killgore with university students (Killgore et al., 2005) approximately 10% of the participants achieved the maximum score within the allotted 2 minutes per page, suggesting a ceiling effect. This ceiling effect was also found in a pilot experiment at the high-level secondary school used for the present experiment. To prevent the negative effect of the ceiling on determining a correlation between age and score, participants in this experiment were allowed only 1 minute per form. This modification resulted in no participant reaching the maximum score. However, by shortening the duration of the test, more emphasis may have been placed on the role of processing speed, with less emphasis placed on the role of learning and memorizing the numerical key code.

The fact that all participants attend the same secondary school poses a limitation as well as an advantage. The limitation lies in the relatively limited diversity among the learning abilities of the participating students. The students at this secondary school all belong to the top 20% with respect to school performance. Thus, the performance demonstrated by the adolescents in this study is likely to be considerably higher than expected for most children of a similar age from the general population. This trend would be in agreement with the results obtained in adults showing that performance on the DOT increased with educational level (Killgore & Gogel, 2014). The increase in Score with grade observed in the present adolescent study also strengthens this expectation. The advantage of having all participants attending the same school is that we will be able to longitudinally assess their visuospatial performance as a follow-up to the present cross-sectional design.

Unfortunately, it was not possible to obtain additional neuropsychological measures of visuospatial or other cognitive abilities. These measures could have provided further validation for the DOT, in addition to the validation already performed by Killgore (Killgore et al., 2005; Killgore & Gogel, 2014). However, the present experiments were conducted during school hours; thus, the available time per experiment was limited. Nonetheless, our results are similar to reported studies using other tests, with respect to their dependence on age and independence of sex. We decided not to counterbalance the order of the two forms. This choice is unlikely to have an impact on our findings as both forms are equally difficult (Killgore et al., 2005). Finally, this study was limited to healthy adolescents. Performances on the DOT by neurological patients (Killgore et al., 2005) was worse than that of healthy controls.

In conclusion, we observed that the visuospatial performance of adolescents increases with age and is independent of sex. The results obtained with the DOT, administered either in an individual or group setting, are in agreement with other studies using more elaborate tests, such as the Block Design test.

Moreover, because the DOT can be easily administered to a group it can, for instance, be utilized in the preliminary testing of school-aged children prior to formal testing for school placement. Collectively, these advantages make the DOT a simple and effective way to assess visuospatial ability, even when the participants are restless young adolescents who would rather conquer the world than sit still for a psychological test.

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3. Performance on Tasks of Visuospatial Memory and Ability: A Cross-Sectional Study in 330 Adolescents Aged 11 to 20

Published

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Abstract and Keywords

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: Visuospatial memory, Non-verbal memory, Visuospatial ability, Design Organization Test (DOT), Adolescence, Development, Cognition

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 et al., 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, 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 shown 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 non-verbal (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, to represent phonologically are used. Many models have been proposed to describe the difference in performance between tasks. For example, Miyake et al. (Miyake, Friedman, Rettinger, Shah, & 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 non-verbal (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 (Crone et al, 2006; Casey et al, 2005), 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 (Burnett 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, 2013). 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; D. 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, Gathercole, & Pickering, 2006; Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Cestari, Lucidi, Pieroni, & Rossi-Arnaud, 2007) and in groups, with performance collapsed and averaged over various age ranges (Conklin, Luciana, Hooper, & Yarger, 2007; Gathercole, Pickering, Ambridge, & Wearing, 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, Friedman, Rettinger, Shah, & Hegarty, 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. (2001).

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 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.

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 et al, 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 thirty-six.

Materials

All thirty-six 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 thirty-six 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 x 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 x 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 minutes.

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. (2005). 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 (Killgore, Glahn, & Casasanto, 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 3.1). 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 two minutes 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.

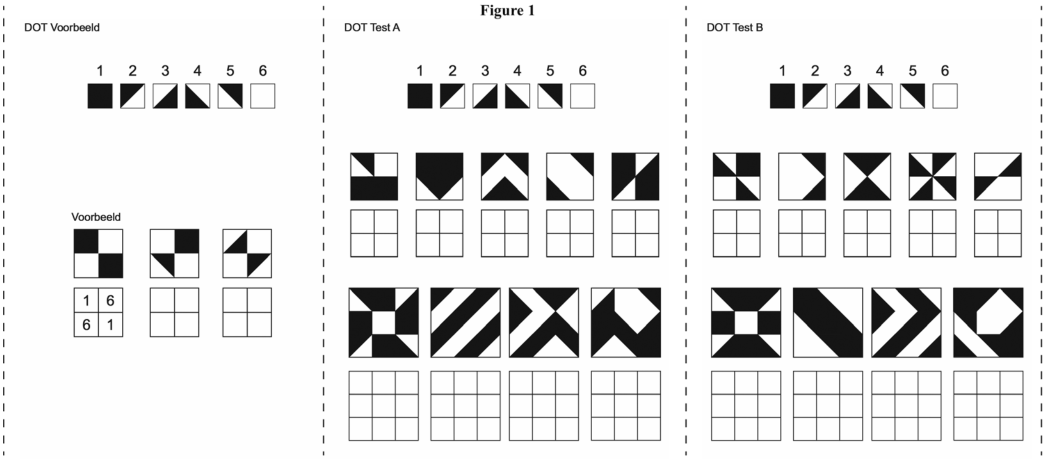

Figure 3.1 – The Design Organization Test (DOT) consists of a practice form labeled 'DOT Voorbeeld' (which is Dutch for 'DOT example') and two forms labeled 'DOT Test A' and 'DOT Test B'. At the top of each form, each pattern is combined with a specific numerical code.

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 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; Table 3.1) of which 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).

Table 3.1: Age and gender distribution of the population per schoolyear

Schoolyear	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)

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 memroy 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 3.2A); 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 $r = 0.71$, $p < 0.001$).

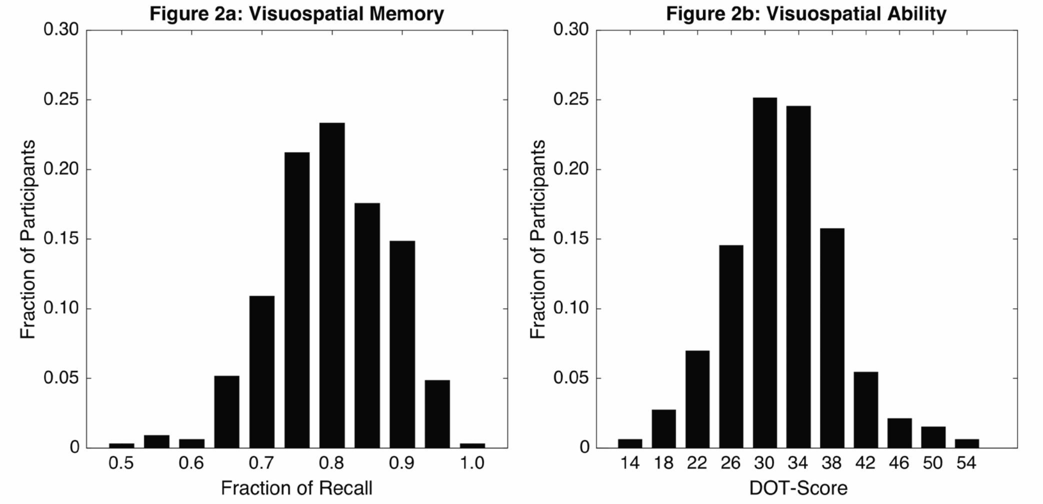

Figure 3.2 - Frequency distribution of the participants' performance. A: Fraction of recall on the visuospatial memory task. B: Score on the visuospatial ability task (DOT).

As expected, the longer sequences were correctly reproduced less often than the shorter sequences (Table 3.2). 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 between15.4 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 3.2) ($F(4) = 864$, $p < 0.001$, $\eta^2 = 0.724$). A post hoc test showed that the reproduction times for all sequence length combinations were highly significantly different (with t varying between 10.1 and 51.3, all $p < 0.001$).

Table 3.2 – 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, 0.022]	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

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 3.2B). 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 ($M_{\text{male}} = 0.47$, *SD* = 0.83 vs. $M_{\text{female}} = 0.39$, *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 3.3B).

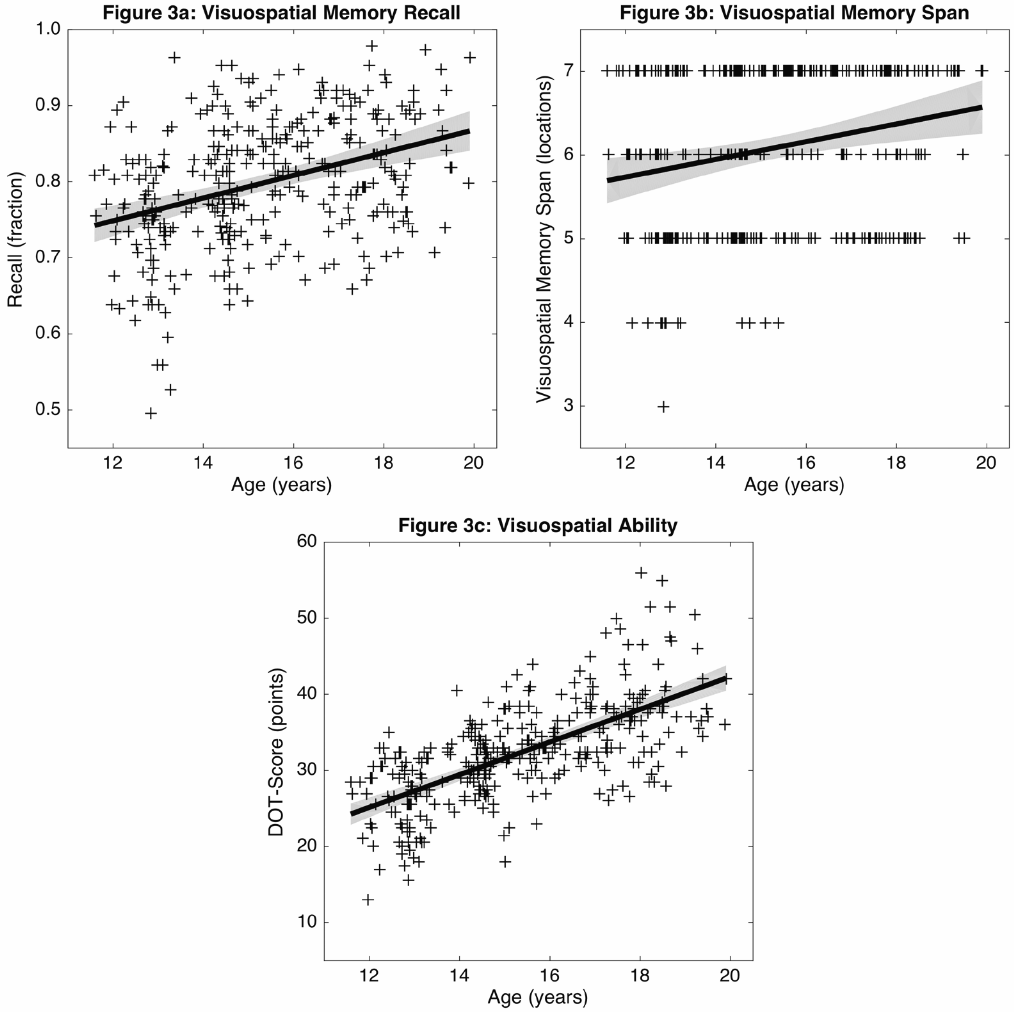

Figure 3.3 – Performance throughout adolescence. Each point represents an individual participant. Gray areas depict 95% confidence intervals. A: Fraction of recall (i.e. the fraction of cued locations that were correctly reproduced). B: Visuospatial Memory Span. C: Score on the Design Organization Test.

The fraction of correctly reproduced sequences per sequence length was positively correlated with age for all sequence lengths (Table 3.2). 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 3.2).

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

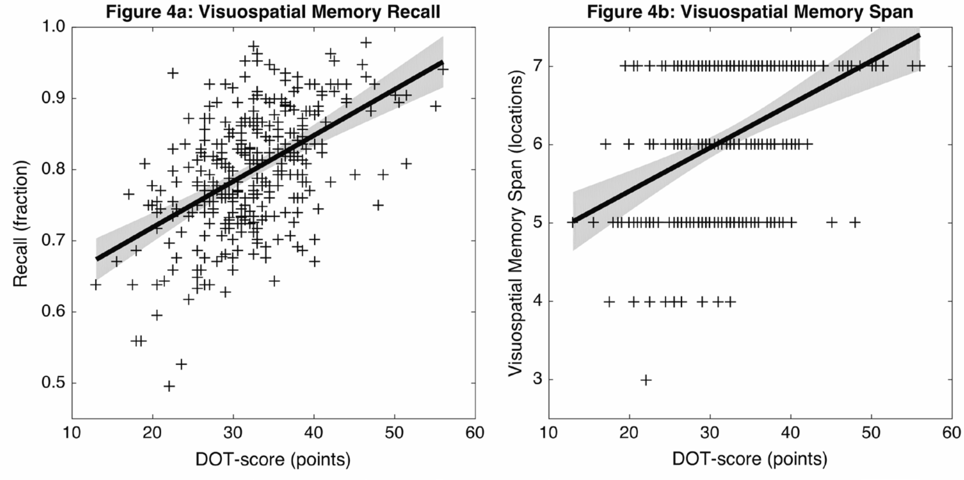

Figure 3.4 – Performance on the visuospatial memory task versus the score on the Design Organization Test. Gray areas depict 95% confidence intervals. A: Fraction of recall. B: Visuospatial Memory Span.

We found strong and significant correlations between the DOT score and the fraction of recall (Pearson's $r = 0.39$, $p < 0.001$) (Figure 3.4A), 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 3.4B). 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 to increased 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 non-verbal 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, by which our task was a inspired, 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; Farrell 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, 1991b; 1991a). 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; I. C. Mammarella & Cornoldi, 2005)), invention errors (reproducing locations that were not cued; I. C. 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. 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 et al., 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; Carretti, et al, 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, 2013). Although an increasing time demand has been shown to increase the performance difference between the sexes in some tasks (D. 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 thirty-six; 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 thirty-six 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. Therefor, 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 performance 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.

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4. Visual search accelerates during adolescence

Published

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Abstract and Keywords

We studied changes in visual search performance and behavior during adolescence. Search performance was analyzed in terms of reaction time and response accuracy. Search behavior was analyzed in terms of the objects fixated and the duration of these fixations. A large group of adolescents (*N* = 140; 12–19 years; 53% male) participated in a visual search experiment in which their eye movements were recorded with an eye tracker. The experiment consisted of 144 trials (50% with a target present), and participants had to decide whether a target was present. Each trial showed a search display with 36 Gabor patches placed on a hexagonal grid. The target was a vertically oriented element with a high spatial frequency. Non-targets differed from the target in spatial frequency, orientation or both. Search performance and behavior changed during adolescence; with increasing age, fixation duration and reaction time decreased. Response accuracy, number of fixations and selection of elements to fixate upon did not change with age. Thus, the speed of foveal discrimination increases with age, while the efficiency of peripheral selection does not change. We conclude that the way visual information is gathered does not change during adolescence, but the processing of visual information becomes faster.

Keywords: Visual search, adolescence, peripheral selection, foveal discrimination, fixation duration, saccade selection, development

Introduction

Visual search is a common component of many daily tasks, such as finding a specific product in a supermarket or making a peanut butter sandwich (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Land, 2006). In these activities, search can be defined as the task of looking for objects of interest in a cluttered visual environment (Tavassoli, Linde, Bovik, & Cormack, 2009). Two aspects of a visual search task can be assessed: performance and behavior. Search performance relates to the result of the search: how many times a target's presence is accurately determined. Search behavior describes the way the search is executed, for instance, which objects were selected for visual fixation and how long were they fixated upon. In the laboratory, visual search performance and behavior can be manipulated using highly controllable and quantifiable stimuli while measuring eye movement behavior.

In a typical visual search task, the participant must decide whether a designated target is present or absent after looking at various locations in a visual scene. During this search, fixations are interleaved with rapid eye movements, called saccades (Kowler, 2011). While fixating on a particular object, observers collect information from their foveal and peripheral vision (Findlay, 1997; Hooge & Erkelens, 1999; Luria & Strauss, 1975; Zelinsky, 2008). Foveal vision provides detailed information about the currently fixated object (Irwin, 2004), whereas peripheral vision provides low-resolution information that can be used to select the most interesting object to fixate on next. Thus, within a visual search task, two sub-tasks can be distinguished. The peripheral selection subtask is based on information from peripheral vision and is aimed at selecting which elements are interesting to fixate on next given the characteristics of the target. The foveal discrimination sub-task is based on information gained from foveal vision and addresses whether the element in focus is the target. Sensory detection thresholds place limits on the level of spatial detail that can be passed on to the rest of the visual system (Geisler, 1984; 1989). Visual search difficulty increases if targets' characteristics are closer to the detection threshold, and characteristics within a factor of five from the threshold can result in slow search (Verghese & Nakayama, 1994). Some of these thresholds, such as grating acuity and vernier acuity, continue to develop during childhood (Elgohary, Abuelela, & Eldin, 2017; Skoczenski & Norcia, 2002). This might make visual search slower for younger children than older ones, depending on the differentiating characteristic between target and non-target elements.

Adequately performing a visual search involves, in addition to the aforementioned sensory factors, various skills such as object recognition, decision-making and planning, that relate to one or both sub-tasks. However, these skills develop progressively during childhood and adolescence (Crone, 2008). The first skills to mature are those associated with more basic functions, such as sensory and motor processes. Skills associated with top-down behavioral control and performing goal-oriented tasks are not fully matured until late adolescence or perhaps not even until early adulthood (Crone, 2009; Casey, Tottenham, Liston, & Durston, 2005; Giedd et al., 1999).

Previous research shows that visual search performance and behavior differ between children, adolescents, and adults (Plude, Enns, & Brodeur, 1994), and maturation of the aforementioned skills may partly explain these differences. Children between 9 and 15 years of age search faster as their age increases (Seassau & Bucci, 2013). This increase in search speed can be mainly attributed to a decrease in fixation duration with age (Huurneman & Boonstra, 2015; Seassau & Bucci, 2013). In contrast, adults between 25 and 70 years of age search more slowly as they become older (Hoyer, Cerella, & Buchler, 2011; Trick & Enns, 1998). These findings suggest that search performance peaks sometime between 15 and 25 years of age. This suggestion is supported by a study that involved groups of participants who were between 6 and 88 years old (Hommel, Li, & Li, 2004). In this study, late adolescents (15-22 years old) and young adults (23-33 years old) performed faster than the younger and older age groups. In contrast to reaction time, response accuracy shows no significant difference among age groups (Huurneman & Boonstra, 2015; Trick & Enns, 1998). Only one study reported a significant decrease in response accuracy as age increased from childhood (6 years old) to early adulthood (23-33 years old) (Hommel et al., 2004). Unfortunately, these studies compared the average search performance and search behavior of groups of participants in broad age ranges, thus losing information regarding the individual performances. Therefore, the quantitative dependency of search performance or search behavior on age has not been reported.

The aim of the present cross-sectional study was to describe the changes in visual search performance and behavior that occur during adolescence. A population of 140 adolescents, aged twelve to nineteen years, participated in a visual search task. The participants were instructed to answer as quickly and correctly as possible whether the target was present in a search display, and we measured their search performance and behavior. The task consisted of 144 trials, of which half contained the designated target. Stimulus elements were designed to differ from the target in spatial frequency, orientation or both. This approach facilitated the quantification of both speed of foveal discrimination and effectiveness of peripheral selection of fixations. Based on previous studies involving children and adults, we hypothesized that search performance and search behavior would change until late adolescence. Specifically, we expected reaction time and fixation duration to decrease with age and peripheral selection to become more efficient, resulting in a higher fraction of fixations being made on stimulus elements most similar to the target and therefore possibly a higher response accuracy.

Methods

Participants

In this study, 140 adolescents (75 males) volunteered to participate. Participants were recruited from all six grade levels of a secondary school (Gemeentelijk Gymnasium) in Hilversum, The Netherlands. Admittance to this school is reserved for students scoring in the highest 20% on a national educational achievement test, Cito, which is taken during the last year of primary school. The experiments were conducted during school hours. Participation was open to all students, registration was voluntary, and no incentives were provided. All participants asserted that they had normal or corrected-to-normal vision. The study adhered to the Declaration of Helsinki, and participants and their parents signed an informed consent document.

Apparatus

Participants sat in a chair with a footrest in front of an experimental booth (82×82×72 cm h/w/d) of which the inside was painted black. A chin rest was placed at the front of the booth, and a 17" computer monitor was placed in the back. A computer keyboard was placed inside the booth to register responses. Participants could freely move the keyboard so that their arms could rest firmly on the bottom of the booth. A black curtain was drawn behind the participant to prevent reflections on the screen from other light sources. To assist the participants in sitting still and being comfortable, the chair and footrest were adjustable in height. The search displays were presented on the monitor at a resolution of 1280×1024 pixels. The search displays extended to 26.4°×21.4° at a distance of 72 cm between the monitor and participant.

Eye movements were recorded using an SMI Eyelink I system (SensoMotoric Instruments, Montreal, CA) at a frequency of 250 Hz. Search displays were viewed binocularly, but eye movements were recorded only from the left eye and were stored for offline analysis.

Stimuli

We designed search displays to be able to discriminate two essential processes that compose visual search: foveal discrimination of the fixated object and peripheral selection of potential targets (Viviani, 1990). Each search display consisted of a gray background (1280×1024 pixels) containing 36 stimulus elements (Gabor patches, size 0.62°, created in MathWorks MATLAB 2015b, http://www.icn.ucl.ac.uk/courses/MATLAB-Tutorials/Elliot_Freeman/html/gabor_tutorial.html). The stimulus elements were arranged in 6 rows of 6 elements placed around the centers of an invisible 6×6 hexagonal grid (as in Hooge & Erkelens, 1999). These centers were 4° apart with a random spatial jitter of 0.3°. The target was always a vertically oriented Gabor patch that had a spatial frequency of 8.19 cycles/° (Figure 4.1). Half of the search displays had no target present, and the other half had one target present. In the displays with a target present, the target appeared once at each of the possible 36 locations.

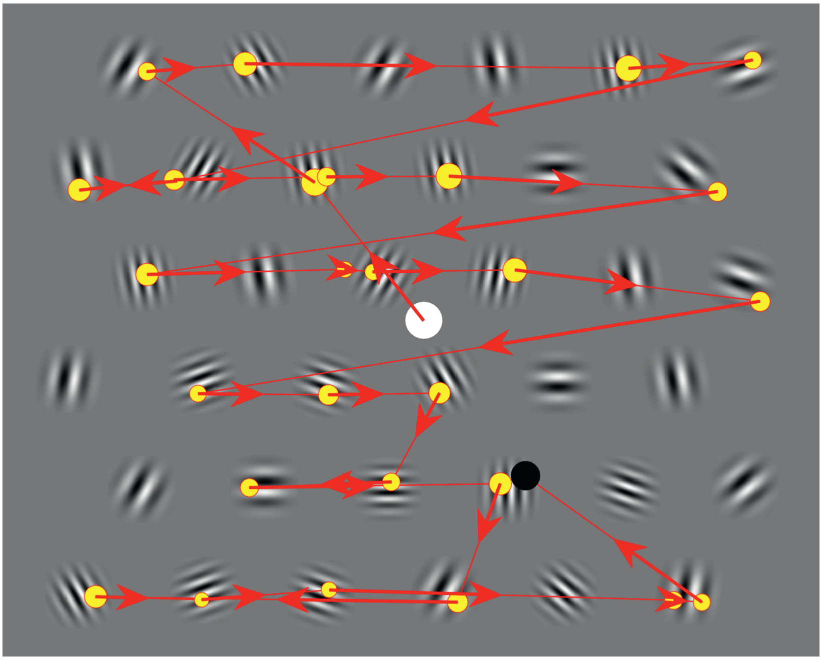

Figure 4.1 – Example of a mixed-frequency display with the target present. In this picture, the stimulus elements have been enlarged for visibility purposes. The target is located at the second row from the bottom, the third element from the right. Drawn upon the search display are the fixations (the radius of the dots is proportional to the fixation duration) and scan path of one of the participants. The white dot was the first fixation; the arrows show the temporal order in which the next fixations were made; and the black dot was the last fixation. Here, we see that the first time the participant fixated upon the target, he did not recognize it. He continued the search and ended it by fixating on the target once again and correctly responding: 'target present'. In this path, most of the LSF elements were skipped and most of the HSF elements were fixated upon.

In 72 of the 144 search displays (called single-frequency displays), the non-target elements were Gabor patches that had the same high spatial frequency as the target but differed from the target in orientation. We will refer to such elements as high spatial frequency (HSF) elements. In the other 72 displays (mixed-frequency displays, Figure 4.1), 18 of the 36 elements had a different orientation than the target as well as a lower spatial frequency (LSF) of 4.82 cycles/°. These LSF elements were randomly placed over the possible 36 locations. The two different spatial frequencies were chosen because they are distinguishable by peripheral vision (Wu and Kowler, 2013; Hooge and Erkelens, 1999) and thus provide a peripheral selection task. The orientation of each of the non-targets in both display types was randomly chosen and varied between ± 10°, ± 30°, ± 50°, ± 70° and ± 90° from the vertical. The different orientations were chosen to manipulate the difficulty of the foveal discrimination task (Wu and Kowler, 2013).

The results of the trials using the mixed-frequency displays enabled us to determine the speed of the foveal discrimination task and the efficiency of the peripheral selection task. In the single-frequency displays, all elements had the same spatial frequency as the target, and no peripheral selection could be made on that basis. We used the results of the trials with single-frequency displays to check whether possible age effects in the speed of foveal discrimination were influenced by the presence of the peripheral selection task.

Procedure

The participants were first shown examples of a mixed-frequency display and a single-frequency display on paper, and both displays contained the target. The participants received verbal instructions regarding the task details, various stimulus elements and target. The task was verbally explained as follows: "Indicate as quickly and accurately as possible whether the target is present or absent. If you find the target, press the 'arrow up' key, and if you decide that the target is not present, press the 'arrow down' key".

After the instructions, the participants were positioned in front of the computer monitor. Their head was placed in a chinrest, and the eye tracker was placed on their head. The participants performed four practice trials, i.e., one of both display types (mixed- or high-frequency) with the target present or absent. The experimenter verified the responses and reminded the participant of the target properties when the target was missed or falsely identified as being present. The practice trials were followed by the 144 experimental trials. A nine-point eye movement calibration and validation procedure was performed at the beginning of both the practice trials and experimental trials. Each new trial was preceded by a drift correction to correct for possible changes in the position of the eye tracker. This correction was done using a fixation circle with a diameter of 0.5° in the middle of the screen on which a participant had to fixate while pressing the spacebar. Upon pressing the spacebar, the screen went blank, and after a random delay of 0.5 to 2.0 s, the search display appeared. The trial ended when the participant responded or after 30 s, if no response was given. The total duration of the task, including explanation and practice, was approximately 45 minutes. Eye movement recordings, display presentations, keyboard handling and timing were controlled by custom-written scripts in Experiment Builder (SR Research, version 1.10.165, on an Apple Macintosh computer).

Data Analysis

The data from four participants who ended the task prematurely were discarded before analysis. Three of these participants (2 males, 1 female) reported neck pain and headache, and the fourth participant (male) was not able to sit still after finishing half of the trials, causing the eye tracker to lose calibration. Additionally, individual trials that had no response within 30 s were discarded before analysis; this happened in only nine trials (of 19584 trials in total, 0.046%). The age of the participant used in the analysis was the actual age in days on the day of participation.

Search performance quantified for each participant by measuring the reaction time and response accuracy. The reaction time per trial was the time measured from the onset of showing the search display until the moment the participant pressed one of the arrow keys. Reaction times were averaged over all trials as well as separately for each of the four different combinations of display type (mixed- and single-frequency displays) and target presence (present and absent). Response accuracy was defined as the proportion of trials in which the participant responded correctly and was also calculated over all trials as well as separately for each of the four different combinations of the display type and target presence.

For the *search behavior analysis*, only correctly answered trials in which the target was absent were considered. Search behavior for each participant was quantified by determining the average fixation duration of all fixations and the average number of fixations per trial. In addition, for each of the 10 different element types, the average fixation duration and the fraction of the total number of fixations on those elements were determined. To determine the search behavior, we processed the recorded eye position as follows. The raw Eyelink I data were first analyzed with the Eyelink Dataviewer 2.4 program, and both the fixation start and end timestamps and the fixation location were extracted from the calibrated eye position data. These data were exported and analyzed using MathWorks MATLAB 2015b on an Apple Macintosh computer. We determined the data quality of the calibrated eye position data for each participant by determining the root mean square (RMS) deviation (RMS) of the inter-sample distances (Holmqvist et al. 2011, page 35).

Fixations located outside the search display were discarded. Furthermore, previous studies (Hooge & Erkelens, 1996; Over, Hooge, Vlaskamp, & Erkelens, 2007; Van Loon, Hooge, & Van den Berg, 2002) have shown that the duration of the first fixation is significantly longer than the subsequent fixations during a visual search, suggesting that different processes occur during the first fixation than during the remaining fixations during the search. Also, the first fixation was a continuation of the fixation on the drift-correction circle in the middle of the screen, where no element was present. Because of these reasons, we removed the first fixation before analysis. We assigned each fixation to the stimulus element closest to the fixation location. Subsequently, consecutive fixations assigned to the same stimulus element were grouped, and the fixation duration on that element, or dwell time (Holmqvist et al. 2011, page 190; Hooge & Camps, 2013), was defined as the sum of the durations of these consecutive fixations.

Statistical analysis:

Pearson correlations were used to determine the associations between age and each separate outcome measure. The difference between two slopes was assessed using the method described by Cohen et al. (2013) and implemented by Soper D.S. (2017) at http://www.danielsoper.com/statcalc. We used Student's t-test to assess the effects of target presence on reaction time, the accuracy of responses and the average number of fixations per trial. Within the trials using the mixed-frequency displays, the effects of stimulus properties (spatial frequency and orientation) on fixation duration and fixation distribution were assessed by means of a repeated-measures ANOVA with two within-subject factors: spatial frequency (2 levels: HSF and LSF) and orientation (5 levels: rotated from the vertical axis by 10°, 30°, 50°, 70° or 90°). Within the trials using the single-frequency displays, this was done by means of a repeated-measures ANOVA with one within-subject factor: orientation (5 levels: rotated from the vertical axis by 10°, 30°, 50°, 70° or 90°). The effect of display type on fixation duration and fixation distribution was assessed for only the HSF elements by a repeated-measures ANOVA with two within-subject factors: display type (2 levels: mixed- and single-frequency display) and orientation (5 levels: rotated from the vertical axis by 10°, 30°, 50°, 70° or 90°). Pearson correlations were used to determine the association between reaction time and response accuracy and between the different outcome measures of search performance and search behavior as described above.

Statistical analyses were performed using IBM SPSS statistical software (version 22) on an Apple Macintosh computer. The reported values are the means and standard deviations or, in the case of a linear regression, the slope and the 95% confidence interval. The threshold for significance was set at an alpha level of 0.05.

Results

A total of 136 participants completed the task without any problems: 72 males (52.9%, aged between 12.4 and 18.8 years; 15.5 ± 1.92) and 64 females (47.1%, aged between 12.5 and 18.5 years; 15.4 ± 1.96). The individual RMS values of inter-sample distances varied between 0.020° and 0.090° (0.039° ± 0.013°), showing that the eye tracking data were of high quality. No response was given within 30 s in only nine trials (of 19584 trials in total, 0.046%); these trials were discarded.

We first report all results concerning the trials using mixed-frequency displays. At the end of the results section, we compare our findings with the results from the trials using single-frequency displays.

Reaction time: Reaction time was significantly correlated with age ($r = 0.207$, $p = 0.015$), and reaction time decreased 0.150 s per year (95% $CI = [-0.270, -0.029]$). This decrease was not significantly affected by target presence (Figure 4.2; $t(268) = 1.316, p = 0.189$).

As expected, the reaction times were shorter for target-present trials than for target-absent trials (respectively: 5.07 ± 0.10 s; 8.28 ± 1.85 s; $t(135) = 31.25$, $p < 0.001$).

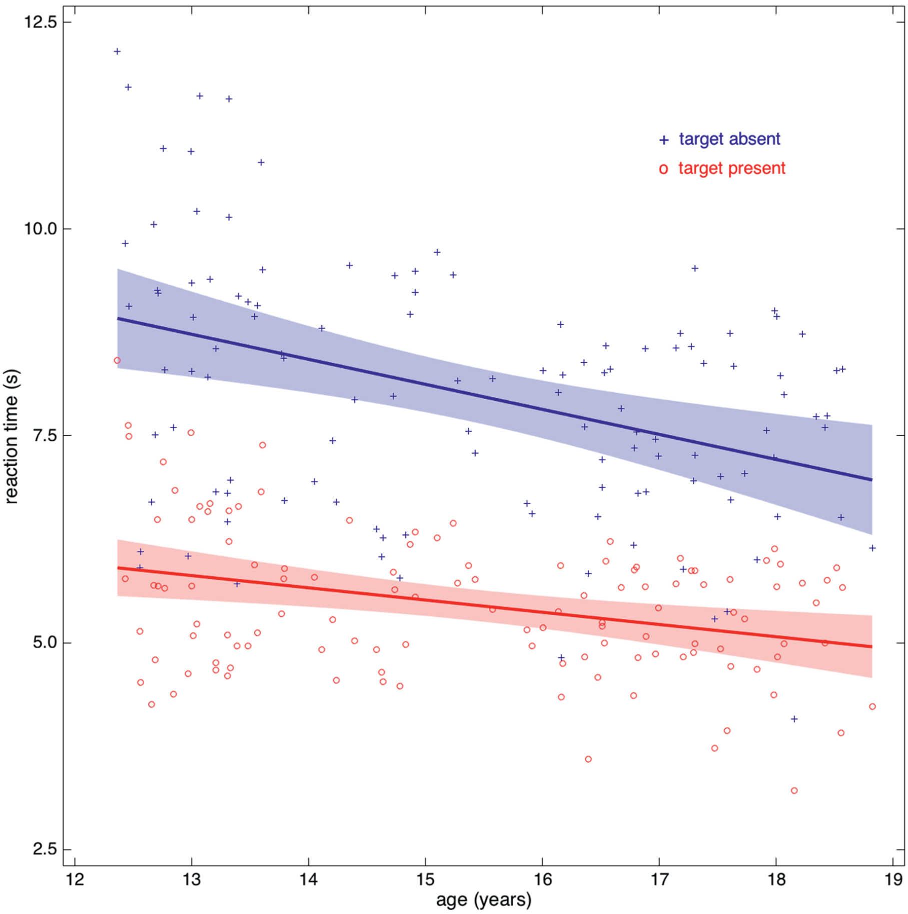

Figure 4.2 – Average reaction time per trial for each participant for correctly answered target-absent and target-present trials. The shaded areas each represent a 95% confidence interval.

Response accuracy: The response accuracy was not significantly correlated with age ($r = 0.032$, $p = 0.715$). Responses were less accurate for the target-present trials (0.809 ± 0.098) than for the target-absent trials (0.974 ± 0.098; $t(135) = 13.53$, $p < 0.001$).

Search performance early and late in the experimental session: The total duration of the tasks of about 45 minutes demanded prolonged attentional focus of the participants. To study possible fatigue or loss of interest, we compared performance measures during the first and second halves of the task. Participants' reaction time and accuracy were both strongly correlated and significantly different between the two halves of the task (reaction time: $r = .788$, $p < .001$; accuracy: $r = .451$, $p < .001$). During the second half of the trials, reaction time was shorter than during the first half of the trials (first half: 8.89±2.11 s; second half: 7.71±1.77 s; Cohen's $d = .605$, $t(135 = 10.559, p < .001)$, and accuracy was lower (first half: .90±.08; second half: .88±.08; Cohen's $d = .250$, $t(135 = 2.428, p < .001)$.

Fixation duration (Figure 4.3A, B): The average fixation duration was significantly correlated with age ($r = 0.306$, $p < 0.001$), with a slope of the fixation duration versus age of -4.93 ms per year (95% *CI* [-8.55, -2.31]). This slope was not significantly affected by spatial frequency (HSF: slope = -5.818, 95% *CI* = [-8.747, -2.890]; LSF: *slope* = -2.849 ms, 95% *CI* = [-5.153, -0.545]; $t(268) = 1.86$, $p = 0.064$) or orientation (the largest difference in slopes was between HSF-10° and HSF-90° and was not significant (HSF-10° slope = -8.278, 95% CI = [-12.555, -4.002]; HSF-90° slope = -4.180, 95% CI = [-7.031, -1.330]; $t(268) = 1.58$, $p = 0.116$; all other combinations of orientations: $t(268) < 1.429$ and $p > 0.154$).

Spatial frequency had a significant effect on the fixation duration, and HSF elements were fixated upon significantly longer (263 ± 34.5 ms) than LSF elements (211 ± 26.8 ms). We also found that orientation had a significant and strong effect on fixation duration on HSF elements but not on LSF elements (respectively: Figure 4.3A, $F(4,132) = 99.4$, $p < 0.001$, $\eta^2 = 0.751$; Figure 4.3B, $F(4,132) = 2.17$, $p = 0.076$, $\eta^2 = 0.062$). Fixation duration was strongly and positively correlated with reaction time ($r = 0.517$, $p < 0.001$) but not response accuracy ($r = -0.139$, $p = 0.106$).

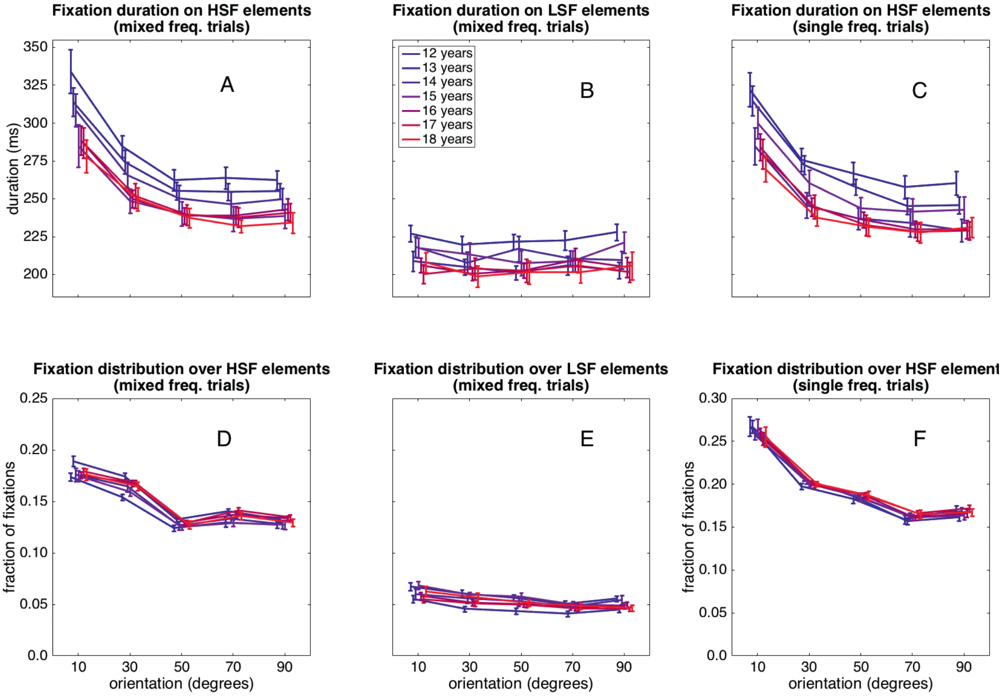

Figure 4.3 – Results concerning the mixed-frequency trials are depicted in: fixation duration on HSF (3A) and LSF (3B) elements and fixation distribution over HSF (3D) and LSF (3E) elements. For the single-frequency trials the fixations durations on HSF elements are depicted in figure 4.3C and the fixation distribution over the HSF elements with different orientations in 4.3F. Although all calculations were performed using the actual age in days of the participants, for clarity in these graphs, the participant sample was binned by year of age. In order to make the standard deviation more clearly visible, the curves have been shifted slightly left and right from the position denoting the angle of orientation.

Number of fixations: The number of fixations was not significantly correlated with age ($r = -0.037$, $p = 0.667$). The number of fixations was lower for target-present than for target-absent trials (13.66 ± 2.92 and 25.80 ± 5.14, respectively; $t(135) = 39.2$, $p < 0.001$). The number of fixations was strongly and positively correlated with reaction time ($r = 0.844$, $p < 0.001$) as well as with response accuracy ($r = 0.461$, $p < 0.001$).

Distribution of fixation locations (Figure 4.3C, D): We found no significant correlation of age with the distribution of fixations over the two spatial frequencies ($r = 0.049$, $p = 0.573$) or over the five different orientations (HSF elements; $-0.028 < r < 0.076$, $0.381 < p < 0.743$; LSF elements; $-0.090 < r < 0.019$, $0.299 < p < 0.915$). Spatial frequency and orientation did have a significant effect on the distribution of fixations with more fixations on elements being more similar to the target. Spatial frequency had a strong effect on the distribution of fixations, with a proportion of 0.737 ± 0.061 of the fixations being made on HSF elements. Orientation also had a significant effect on the distribution of fixations, with more fixations being made on the elements most similar to the target. This effect, though, was much stronger for HSF elements than LSF elements (Figure 4.3C, $F(4) = 567, p < 0.001, \eta^2 = 0.808$; and Figure 4.3D, $F(4) = 57.5, p < 0.001, \eta^2 = 0.299$, respectively).

Comparison of results between display types: Within the single-frequency trials, we found the same correlations of age and the individual outcome measures to be significant as within the mixed-frequency trials. In these trials, reaction time ($r = 0.218$, $p = 0.011$) and fixation duration ($r = 0.381$, $p < 0.001$) significantly decreased as age increased. Comparable to the results in the mixed-frequency trials, in the single-frequency trials, the decrease of fixation duration with age was not affected by the orientation with the largest difference, found between HSF-10° and HSF-70°, not being significant (HSF-10° $slope = -8.985$, 95% $CI = [-12.846, -5.123]$; HSF-70° $slope = -4.751$, 95% $CI = [-7.423, -2.079]$; $t(268) = 1.784$, $p = 0.076$); all other combinations of orientations of HSF-elements: $t(268) < 1.759$ and $p > 0.080$). No significant correlation was found between age and response accuracy ($r = 0.058$, $p = 0.499$), age and number of fixations per trial ($r = -0.054, p = 0.530$) or age and distribution of fixations over the different orientations (all orientations: $r < 0.076, p > 0.381$).

The average fixation duration on HSF elements was slightly but significantly shorter in the single-frequency trials (262 ± 34.1 ms) than in the mixed-frequency trials (266 ± 35.0 ms; Cohen's $d = .115$, $t(135) = 21.1, p < 0.001$). Finally, the distribution of fixations showed a slightly stronger effect for orientation in the single-frequency trials ($F(4,132) = 322, p < 0.001, \eta^2 = 0.907$) than in the mixed-frequency trials ($F(4,132) = 168, p < 0.001, \eta^2 = 0.836$).

Discussion and Conclusions

The present cross-sectional study aimed to evaluate changes in search performance and search behavior during the adolescent period. A group of 136 adolescents (12 to 19 years of age) successfully performed a visual search task while eye movements were measured with an eye tracker. Within 144 search displays, they had to determine whether a designated target was present or not. The results showed that search performance increased during adolescence, and searches were performed faster while maintaining the same level of response accuracy. Analysis of search behavior showed a decrease in fixation duration with age while neither the number of fixations nor the selection of fixation locations changed.

The reaction time decreased significantly with age (Figure 4.2). Earlier studies with younger children also reported a decrease of reaction time with age (Huurneman & Boonstra, 2015; Seassau & Bucci, 2013) and an increase of reaction time with age for older adults (Hommel et al., 2004; Trick & Enns, 1998). These findings suggest that reaction time would be shortest during the period between 15 and 33 years old. Our results show that the decrease of reaction time continues at least up to the age of 19.

Additionally, fixation duration decreased significantly with age (Figure 4.3A, B). This decrease has previously been shown to be present in younger children (Huurneman & Boonstra, 2015; Seassau & Bucci, 2013). Our research extrapolates this finding up to the end of the adolescent period and provides a quantitative estimate of this decrease as approximately 5 ms per year. The detection limit for grating acuity for ten- to twenty-year-olds has previously been reported to be in the range of 27 to 33 cycles/° (Skoczenski & Norcia, 2002). The finest grating used in this study is 8.19 cycles/°. However, search times have been shown to increase at factors of up to five from detection limits (Verghese & Nakayama, 1994), and grating acuity might not yet have stabilized at adolescence (Skoczenski & Norcia, 2002). Therefore, grating acuity may explain part of the longer fixation durations for younger participants for elements similar to the target. To determine this, individual grating acuity levels are necessary, but unfortunately, we do not have these measurements. The difficulty of the foveal discrimination task did not significantly influence the decrease in fixation duration with age. This might suggest that this effect of age is a result of the acceleration of a process different from foveal discrimination. This notion is supported by an earlier study that also shows an increase in processing speed with age in tasks other than visual search, such as simple mental calculations and image matching (Kail, 1991a; 1991b). Based on our results, we conclude that the speed of the foveal discrimination sub-task increases until the end of adolescence independent of the difficulty of the task.

Even though the difficulty of the foveal discrimination did not influence the change in fixation duration with age, it did influence the fixation duration itself as well as the distribution of the fixations over the different elements (Figure 4.3). Elements more similar to the target were fixated upon more often and were fixated upon for longer. The increase of fixation duration as target similarity increased is consistent with reports from earlier studies (Vlaskamp & Hooge, 2005, Hooge & Erkelens, 1996). Spatial frequency had the strongest effect on fixation duration. Orientation also affected the fixation duration but only when the spatial frequency was the same as that of the target. Furthermore, the effect of spatial frequency on fixation duration was much stronger than the effect of orientation. Our data suggest that for adolescents, a difference in spatial frequency between the fixated element and the target was easier to discriminate than a difference in orientation. Many models describing fixation durations (McDonald, 2006; Reddi, 2003; Reddi & Anderson, 2009) are based on the assumption that during fixations, visual information is gathered until a certain threshold level of information is reached. Shorter fixation durations, in these models, might result from less time being required to collect enough information to reach the information threshold, for instance because the fixated object is easily distinguished from the target or because of a lowered threshold of the accuracy to be reached. Several of our results support the hypothesis of flexibility in fixation duration rather than in the stringency of accuracy criteria. First, we found that fixation durations differ for fixation of the different types of elements. Fixation durations were longer when the element fixated more closely resembled the target. Furthermore, since all participants were shown the same search displays, their tasks were of equal difficulty. Though the average reaction times and fixation times were shorter for older children than for younger children, we found no significant difference in accuracy, neither at the trial level (response accuracy) nor at the fixation level (the fraction of saccades made to high-spatial frequency elements). These findings support the suggestion that throughout adolescence, the criterion for terminating a fixation seems to lie with maintaining a similar threshold for information gathering and thus a similar level of response accuracy and adjusting the fixation duration accordingly.

Elements more similar to the target were fixated upon more often, and this distribution of fixations did not change significantly with age. For all ages, elements with the same spatial frequency as the target were fixated upon about three times as often as the ones with a different spatial frequency. This result suggests that our manipulation of the spatial frequency did result in peripheral selection of fixation locations. To a much lesser extent, orientation information was also used to select the next element for fixation. Peripheral selection has been studied before in adults. By manipulating various element characteristics, such as color (Findlay, 1997), form (Luria & Strauss, 1975), orientation (Zelinsky, 1996) and gap and line width (Hooge & Erkelens, 1999). Our results suggest that efficiency of the peripheral selection sub-task is already fully developed at the age of twelve.

By comparing the results of two different types of trials (using either mixed- or single-frequency displays), we found that the significant age effect on the speed of the foveal discrimination sub-task was not influenced by the presence of the peripheral selection sub-task. Independent of age, we did find that the fixation durations were slightly shorter when the fixated element was surrounded only by elements of the same spatial frequency than when it was surrounded by elements with a mix of different spatial frequencies. This suggests that not only the difficulty of the foveal discrimination task but also the complexity of the peripheral selection task (selection on orientation only versus selection on orientation and spatial frequency) influences the fixation duration. The results of earlier studies are inconclusive as to whether increased fixation duration should be attributed only to the difficulty of the foveal discrimination task (Hooge & Erkelens, 1999) or also to the process connected to the search, i.e., to the selection of the next fixation location (Wu & Kowler, 2013). Since the elements fixated were the same and only the surrounding elements differed in our study, our results tentatively support the latter suggestion, though it should be noted that both reported studies (Wu & Kowler, 2013; Hooge & Erkelens, 1999) were performed with adults while our participants were adolescents. It might be interesting for future research to study whether the effect of the complexity of the peripheral selection sub-task on fixation durations might be different for different age groups.

Correlation of search performance with search behavior showed that the reaction time was strongly and positively correlated with the fixation duration. Both reaction time and fixation duration decreased with age. Previous research with younger children and adults (Huurneman & Boonstra, 2015; Seassau & Bucci, 2013) reported that the decrease in reaction time could mainly be attributed to a decrease in fixation duration with age. Our results show this finding to also be true for adolescents of all ages. Response accuracy was found to be significantly correlated with only the number of fixations, which is also supported by our finding that neither the response accuracy nor the number of fixations was significantly correlated with age. Previous research with young children and adults (Huurneman & Boonstra, 2015; Trick & Enns, 1998) did not specifically correlate these two outcome measures but did report that with age, the number of fixations and the response accuracy both remained at a constant level (which is consistent with our findings for adolescents).

The task used in our research required the participants to sit still and concentrate for more than half an hour and sometimes up to an hour. Our results show that during the second half of the trials, response time was shorter and response accuracy lower than during the first half of the trials. If this had been an effect of fatigue, one would expect search to become less efficient yielding longer reaction times and lower response accuracy. Since our results show, next to decreasing response accuracy, a decrease in reaction times, this suggests more that participants were losing interest in searching the display extensively. We did not ask participants about changes in their motivation during the experiment, so we can only speculate that because of the length of the visual search task, participants lost some interest and motivation. Depending on the aims of future studies, one might consider shortening the length of this task, since our results show that the use of the single-frequency trials alone suffices to reveal the reported effects of age on search performance and search behavior. If the aim of the research is to determine whether peripheral selection might be age dependent in groups of different ages or education levels, only the mixed-frequency search trials need to be used. For future use of this task, we would advise using only one of the two types of search displays in order to reduce the task time by half.

It should be noted that the participants in our study were all students who achieved high scores on a national intelligence test. No previous reports have been found describing a correlation between IQ and search performance or behavior, making it interesting for future studies to determine whether the magnitude of the correlations with age described in this study are comparable with what would occur in children of other IQ levels. A limitation of our study is that it employed a cross-sectional design, whereas a longitudinal approach would allow the assessment of visual search performance and behavioral development in individuals. Another limitation is that we do not have measurements concerning each participant's grating acuity, a factor that might have influenced fixation durations. For future use of this task, especially with children, we would suggest including these measurements, given that grating acuity might not have yet reached a stable threshold during childhood (Skoczenski & Norcia, 2002).

In conclusion, during adolescence, search performance and search behavior change. Speed of foveal discrimination increased with age, while efficiency of peripheral selection did not change with age. Visual search is often an important part of many daily tasks. Our findings suggest that it is the speed with which the visual information is processed that changes with age, not the way it is gathered. Since the processing of visual information is necessary for a large variety of tasks, our findings could tentatively explain why children and adolescents, even up to young adulthood, become faster at all types of daily tasks. Given the large number of fixations made each year, a small decrease in the duration of each fixation could provide much-needed extra time for adolescents to face the difficulties of the ever-increasing complexity of their lives.

5. Developmental changes in visual search are determined by changing visuospatial abilities and task repetition: a longitudinal study in adolescents

Abstract and Keywords

Using a longitudinal study design, a group of 94 adolescents participated in an experimental session consisting of a visuospatial ability task and a visual search task. Participation was during four consecutive years with intervals of one year. We analyzed the association between changes in visuospatial ability and changes in visual search performance and behavior and estimated additional effects of age and task repetition. Visuospatial ability was measured with the Design Organization Test (DOT). Search performance was analyzed in terms of reaction time and response accuracy. Search behavior was analyzed in terms of the number of fixations per trial, the saccade amplitude and the distribution of fixations over elements that share visual characteristics with the target to a more or lesser extend. We found that both the increase in age and the yearly repetition of the DOT had a positive effect on visuospatial ability. We confirm the acceleration of visual search during childhood that has been found in cross-sectional studies, but show that this acceleration can be explained by the increase in visuospatial abilities with age during adolescence. With the yearly repetition, visual search became faster but also more accurate, while fewer fixations were made with larger saccade amplitudes. Additionally, selecting the next element for fixation became more efficient with task repetition. The combination of increasing visuospatial ability and task repetition make visual search more effective and might increase the performance of many daily tasks during adolescence.

Keywords: Visual search, adolescence, peripheral selection, foveal discrimination, fixation duration, saccade selection, development, Design Organization Test, visuospatial ability, longitudinal

Introduction

From infancy to young adulthood, children develop and improve upon many different abilities, such as social cognition, organization, decision making and planning (Crone 2008; Blakemore, 2008; Spear, 2000; Yurgelun-Todd, 2007). A common behavioral component of many of these activities is the need to search for visual information (Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Land, 2006). During visual search, fixations are interleaved with rapid eye movements, called saccades (Kowler, 2011). While fixating on a particular object, observers may collect information from their foveal and peripheral vision (Findlay, 1997; Hooge & Erkelens, 1999; Luria & Strauss, 1975; Zelinsky, 2008). Foveal vision provides detailed information about the currently fixated object (Irwin, 2004), whereas peripheral vision provides low-resolution information that can be used to select the most interesting object on which to fixate next.

In a typical search task, participants must determine as quickly and as accurately as possible whether a certain target is present in a display. Visual search can easily be studied in a lab environment where performance and behavior can be assessed. Search performance relates to the result of the search: how quickly and how accurately the target's absence or presence is determined. Search behavior describes the way the search is executed, for instance, which objects were selected for visual inspection and how long were they fixated upon.

Visual search performance and behavior change with age. In a previous study, using a cross-sectional design with adolescents between 11 and 20 years old, we observed that search became faster with age (shorter fixation times and shorter reaction times), while accuracy remained the same (Burggraaf, van der Geest, Frens, & Hooge, 2018). Visual search times already start decreasing at pre-adolescence and subsequently increase during late adulthood (Plude & Hoyer, 1986; Plude, Enns, & Brodeur, 1994; Hoyer, Cerella, & Buchler, 2011; Trick & Enns, 1998). The decreasing of visual search times is largely a result of shorter fixation durations, while the number of fixations does not change significantly with age (Burggraaf et al., 2018; Huurneman & Boonstra, 2015; Seassau & Bucci, 2013). Response accuracy in visual search does not differ significantly between children of different ages (Burggraaf et al., 2018; Huurneman & Boonstra, 2015; Trick & Enns, 1998). The combination of shorter average reaction times for older children than for younger children with no significant difference in accuracy, suggests that the criterion for terminating a fixation seems to lie with maintaining a similar threshold for information gathering and thus a similar level of response accuracy and adjusting the fixation duration accordingly.

All of the aforementioned cross-sectional studies correlate differences in visual search to changes in age but do not take into account that age-related changes in other visually related abilities might mediate these changes, such as visuospatial abilities that include part-to-whole integration and pattern recognition (Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Linn & Petersen, 1985). These abilities improve with age (Burggraaf, Frens, Hooge & van der Geest, 2015; 2017; Eisner, 1972; Kohs, 1920; Shah & Frith, 1993); however, the development of visuospatial skills varies between subjects, thereby hampering the proper assessment of the relationships between age, visuospatial skills and visual search behavior in a cross-sectional design.

In the current longitudinal study, we examined individual performance and behavior in a visual search task and in a visuospatial ability task in a single experimental session. These experimental sessions were repeated during four consecutive years with intervals of one year. Visuospatial ability was measured with the Design Organization Test (DOT; Killgore & Gogel, 2014; Killgore, Glahn, & Casasanto, 2005). Based on the results of our cross-sectional study, we hypothesize that visuospatial ability as measured with the DOT will increase with age. Visual search performance and behavior were measured using a task consisting of 144 different displays, of which 50% had one target present). Search behavior was analyzed in terms of the number of fixations per trial, the saccade amplitude and the distribution of fixation locations over the elements that share visual characteristics with the target to a more or lesser extend . Based on our earlier work (Burggraaf et al, 2015; 2017), we hypothesize that visuospatial ability increases with age and that during visual search the speed with which the visual information is processed increases, but the manner in which this information is gathered does not vary.

Methods

Participants

Participation in this longitudinal study was open to students of a secondary school in Hilversum, the Netherlands (Gemeentelijk Gymnasium Hilversum). All participants had scored in the highest 20% on a national educational achievement test, Cito, during the final year of primary school. The students whose results are reported in this study performed the experiment for the first time while attending any of the first four (of a total of six) grade levels. These participants form a subgroup of the population reported upon in a previous cross-sectional study (Burggraaf et al., 2018). Registration was voluntary, administration of the tasks was during school hours, and no incentives were provided. All participants were confirmed to have normal or corrected-to-normal vision. This study adhered to the Declaration of Helsinki, and participants and their parents signed an informed consent document. Participants performed both a visuospatial ability task and a visual search task multiple times, once per year, a maximum of four times resulting in a number of repetitions between 1 and 4.

Visual search task

To determine visual search performance and behavior, we used the same setup and procedure used in our previous cross-sectional study, which are summarized below (for more details, see Burggraaf et al., 2018).

Eye movements were recorded using an SMI Eyelink I system (SensoMotoric Instruments, Montreal, CA). The search displays extended 26.4°×21.4° at a distance of 72 cm between the monitor and participant, and a chin rest and footrest were provided for added stability.

Each search display consisted of 36 Gabor patches (size 0.62°) arranged in 6 rows of 6 elements placed around the centers of an invisible 6×6 hexagonal grid (see also Hooge & Erkelens, 1999). These centers were set 4° apart, with a random spatial jitter of 0.3°. The target was always a vertically oriented Gabor patch that had a spatial frequency of 8.19 cycles/° (Figure 5.1). Half of the search displays had no target present, and the other half had one target present. In the displays with one target present, the target appeared once at each of the 36 possible locations.

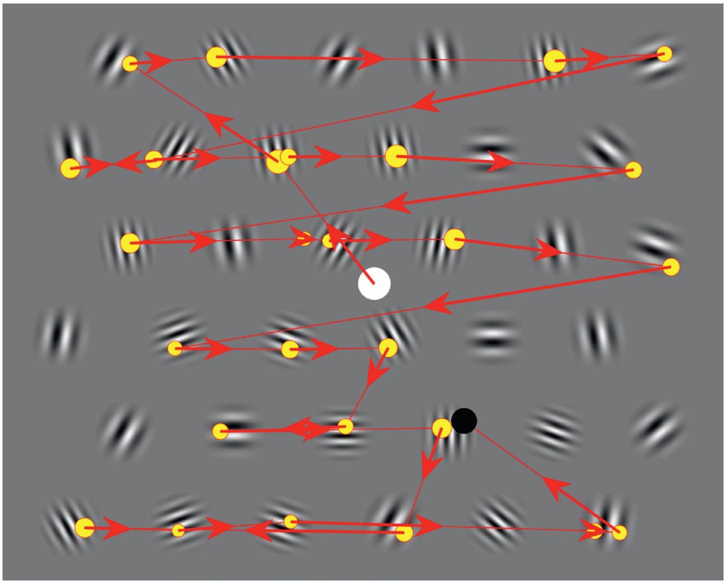

Figure 5.1 Example of a mixed-frequency display with the target present. All elements have been enlarged for visibility. The target is the third element from the right in the second row from the bottom. The element on the top-left of the display is a low-spatial frequency (LSF) element, the element on the bottom-let of the display is a high-spatial frequency (HSF) element. The orientation of each of the non-targets randomly varies between ± 10°, ± 30°, ± 50°, ± 70° or ± 90° from the vertical. The scan path of one of the trials is shown here. The white dot is the location of the first fixation; the black dot, the last; and the yellow dots, the intermediate fixations. The radius of the dots is proportional to the fixation duration, and the arrows indicate the temporal order in which the fixations were made. In this path, most of the LSF elements were skipped, and most of the HSF elements were fixated upon, suggesting the use of visual information from peripheral vision to largely limit the fixations to elements with a spatial frequency equal to that of the target.

In 72 of the 144 search displays, we used mixed-frequency displays (Figure 5.1). In these displays, half of the elements had the same high spatial frequency (HSF) as the target but with different orientations. The other half of the elements had low-spatial-frequency (LSF) elements of 4.82 cycles/°, also with different orientations than the target. All non-targets were randomly placed over the 36 possible locations. The other half of the trials used single-frequency displays with all non-targets being HSF elements. These single-frequency displays formed part of a cross-sectional study we performed earlier. These trials yielded no additional insights into visual search. Nevertheless, we decided to retain the trials as part of the longitudinal experiment and not alter the experiment. Thus, we can include the results of the cross-sectional study followed by an additional three repetitions.

The participants received verbal instructions regarding the task details, the various stimulus elements and the target. The task was verbally explained in Dutch. The English translation of the explanation is as follows: "Indicate as quickly and accurately as possible whether the target is present or absent. If you find the target, press the 'up arrow' key, and if you decide that the target is not present, press the 'down arrow' key". A calibration and validation procedure was followed by four practice trials and then the 144 experimental trials. Each trial was preceded by drift correction using a fixation circle in the middle of the screen. A trial ended when the participant responded or after 30 s if no response was given. The participant received no feedback from the program or from the experimenter regarding the accuracy of their answers. The total duration of the task, including the explanation and practice, was approximately 45 minutes. Custom-written scripts in Experiment Builder (SR Research, version 1.10.165, on an Apple Macintosh computer) controlled eye movement recordings, display presentations, keyboard handling and timing.

Search performance was quantified for each participant by measuring reaction time and response accuracy. The reaction time for each trial was the time measured from the onset of the search display until the moment the participant pressed one of the arrow keys. Reaction times were averaged over all trials. Response accuracy was defined as the proportion of trials in which the participant responded correctly and was also calculated over all trials. For these outcome measures, target-absent and target-present trials were combined.

Search behavior for each participant was quantified by determining the average number of fixations and the average amplitude of the saccades (in degrees) per trial where the saccade amplitude might be an indication of the size of the area of which the visual system can analyze information during a fixation. Also we determined the average fixation duration per trial which we use as a measure of the time needed to analyze the information within the visual field and we quantified the fixation distribution by determining the fraction of fixations made on elements with the same HSF as the target. Thus, a higher fraction could indicate a more efficient use of information from peripheral vision to determine the location of the next fixation. To ensure that multiple fixations had to be made per trial only correctly answered, target-absent trials were used to determine these outcome measures.

Individual trials that had no response within 30 s were discarded. The recorded eye positions were processed as follows. The raw Eyelink I data were first analyzed with the Eyelink Dataviewer 2.4 program, and both the fixation start and end timestamps and the fixation location were extracted from the calibrated eye position data. These data were exported and analyzed using MathWorks MATLAB 2015b on an Apple Macintosh computer.

Fixations located outside the search display as well as the first fixations were discarded. We then assigned each fixation to the stimulus element closest to the fixation location. Subsequently, consecutive fixations assigned to the same stimulus element were grouped, and the fixation duration on that element was defined as the sum of the durations of these consecutive fixations.

Visuospatial ability task

To assess the visuospatial ability of the participants, we used the same, slightly shorter variation of the Design Organization Test (DOT, Killgore et al., 2005; Killgore & Gogel, 2014) we used in our cross-sectional studies (Burggraaf et al., 2015; 2017).

The DOT consists of two test forms and a practice form (Figure 5.2). At the top of the page, a key is provided with a number corresponding to a black-and-white pattern in a square. Participants fill the empty squares of the form with the numbers that correspond to the patterns. In this shorter version of the DOT, participants had one minute to complete each form.

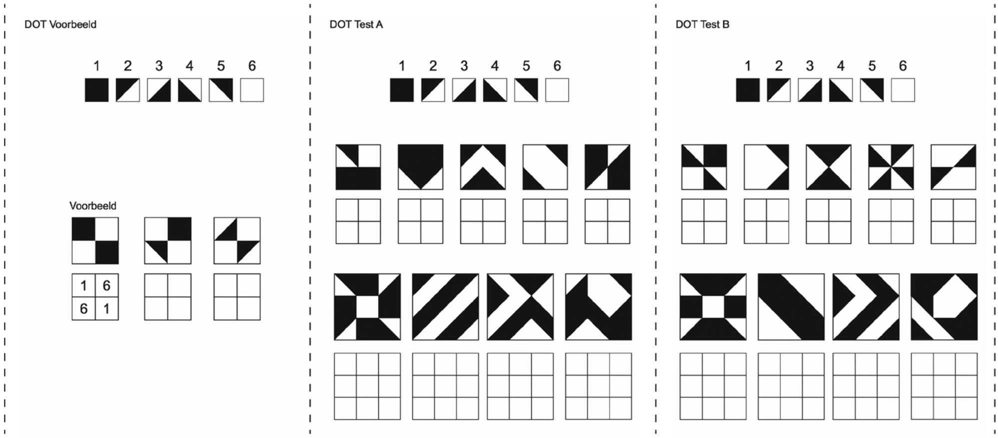

Figure 5.2 – The Design Organization Test (DOT) consists of a practice form labeled 'DOT Voorbeeld' (which is Dutch for 'DOT example') and two forms labeled 'DOT Test A' and 'DOT Test B'. At the top of each form, each pattern is combined with a specific numerical code.

Each participant was verbally informed of the task 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." First, the participant was given an example to fill out without time constraints. The participant was then given exactly one minute to fill out as many squares as possible on form A and, after a brief pause, to do the same for form B. Completing the full task, including the explanation and the completion of the practice form, took an average of 5 minutes.

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

Statistical analysis

Data analysis was performed on the results of participants who participated at least twice. Before analysis, all data from participants who ended the visual search task prematurely were discarded.

For the analysis of the visuospatial ability task, a linear regression model was used. One of the independent variables was the number of yearly repetitions. The number of repetitions could vary between 1 and 4; with 1 being the first time of participation and 4 the maximum of four times the tasks were performed. All repetitions were performed about one year after the date of the first performance, with a maximum variation of two weeks earlier or later than that date. The other two independent variables were the DOT score and age. We analyzed each of the outcome measures of the visual search task using two different linear regression models. One model, called the full model, used the number of repetitions, DOT score and age as independent variables and was used to study which variable(s) had a significant contribution to the model. The other model, called the reduced model, used only the number of repetitions and DOT score as independent variables. We compared the two models to determine whether the full model performed significantly better than the reduced model. We also used a linear model to investigate the association between the accuracy of the responses, the reaction time and the number of repetitions.

Statistical analyses were performed using IBM SPSS statistical software (version 22) on an Apple Macintosh computer. The reported values are the means and standard deviations or, in the case of a linear regression, the slope and the 95% confidence interval. The threshold for significance was set to an alpha level of .05.

Results

A total of 94 participants (55 male; Table 5.1) successfully completed the experiment in at least two consecutive years and 86 (49 male) in three consecutive years. Ultimately, 74 (42 male) participants successfully completed the experiment for four consecutive years.

Table 5.1 – Description of the population during each yearly repetition of the experiment

		Male		Female	
Yearly repetition	N (total)	N	Age (year) mean ± SD (min-max)	N	Age (year) mean ± SD (min-max)
1	94	55	15.2 ± 1.7 (12.4-18.1)	39	14.9 ± 1.5 (12.7-17.3)
2	94	55	16.3 ± 1.7 (13.4-19.1)	39	16.0 ± 1.5 (13.7-18.3)
3	86	49	17.0 ± 1.7 (14.3-19.9)	37	16.9 ± 1.5 (14.7-19.4)
4	74	41	18.0 ± 1.6 (15.2-20.9)	33	17.9 ± 1.6 (15.7-20.5)

Visuospatial ability

We measured visuospatial ability with the Design Organization Test (DOT). The individual scores on this test varied between 16.0 and 56.0 points (Figure 5.3). The average DOT scores increased with each yearly repetition (respectively 32.0 ± 5.7, 36.0 ± 5.8, 37.6 ± 5.7 and 40.3 ± 6.2). A multiple linear regression was performed to predict the DOT score from the number of repetitions and age. These variables significantly predicted the DOT score ($r=.613$, $F(2,345 = 103.729$, $p<.001$). Both variables significantly contributed to the model, with age having a stronger effect than the number of repetitions (both $p<.001$; $\beta_{age} = 500$; $\beta_{repetition} = 174$). On average, the DOT score increased by 1.72 (95% $CI = 1.38, 2.07]$) points per year.

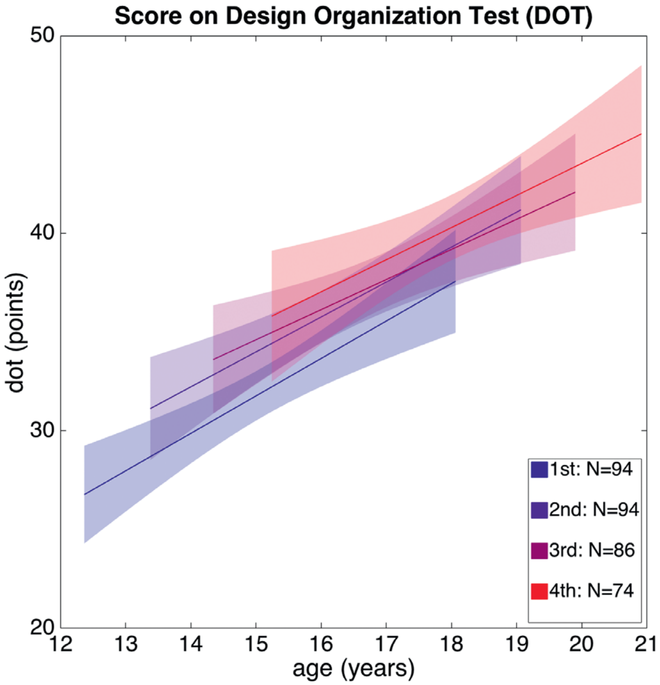

Figure 5.3 – Score on Design Organization Test (DOT) versus age for each yearly repetition. The shaded areas denote the 95% confidence interval.

Visual search

When analyzing the results of the visual search task, we used the following outcome measures: average fixation duration, average number of fixations per trial, average amplitude of saccades and the fraction of fixations made on HSF elements. Using age alone as a predictor, all outcome measures are significantly correlated with age. As discussed in the visuospatial ability section, age is strongly and positively correlated with the DOT score. We analyzed whether the number of repetitions and the DOT score mediate the correlation between age and the outcome measures. To this end, we performed a multiple regression analysis that used age, the number of repetitions and the DOT score as predictors (Table 5.2, full model). Age was not a significant contributor to the model for any of the outcome measures of visual search. The effect of age was mediated by either the DOT score (for the fixation duration), or the number of repetitions (for the response accuracy, the number of fixations per trial, the saccade amplitude and the distribution of fixations) or both (for the reaction time). A model using age, the number of repetitions and the DOT score as predictors did not perform significantly better than the model without age as a predictor (Table 5.2, reduced model). Therefore, when analyzing the results of the visual search tasks, we used only the model with the number of repetitions and the DOT score as predictors, reporting whether either of them or both were significant contributors to the model.

Table 5.2 – Comparison of the full model (predictors: the number of repetitions, the DOT score and age) with the reduced model (predictors: the number of repetitions and the DOT score) in predicting the value of the outcome measures. In the full model, age had no significant contribution to any of the outcome measures.

	$r_{\text{full model}}$	$r_{\text{reduced model}}$ (F(2,345), all p<.001)	$\beta_{\text{DOT-score}}$	$\beta_{\text{repetition}}$
Reaction time	.388	.387 (F=0.338)	-.236, $p < .001$	-.218, $p < .001$
Accuracy	.320	.319 (F=9.535)	-.016, p=776	.326, $p < .001$
Fixation duration	.342	.340 (F=2.594)	-.323, $p < .001$	-.035, p=540
Nr. of fixations	.314	.306 (F=7.844)	-.101, p=078	-.247, $p < .001$
Saccade amplitude	.301	.300 (F=7.006)	-.001, p=984	.300, $p < .001$
Fixation distribution	.234	.232 (F=.781)	.049, p=407	.206, $p < .001$

Visual search performance

Visual search performance was assessed by studying reaction time and response accuracy. The average reaction time per participant decreased with an increasing

DOT score as well as an increasing number of repetitions, and both variables significantly contributed to the model with nearly equal effects (Table 5.2). The average reaction time decreased with each repetition, from 6.96 ± 1.31 s to 5.67 ± 1.27 s (Table 5.3), decreasing on average .285 s (95% $CI = -.428, -.143]$) per repetition. Furthermore, the average reaction time decreased .052 s (95% $CI = -.076, -.028]$) with each one-point increase in the DOT score (Figure 5.4A). A multiple linear regression showed that in the model of the average response accuracy only the number of repetitions, and not the DOT score, contributed significantly to the model (Table 5.2). The average response accuracy increased from .894 ± .059 to .939 ± .042 (Table 5.3), increasing on average .016 (95% $CI = .011, .021]$) per repetitions. Thus, with the repeated execution of the task, the children became faster and more accurate. The increasing DOT score of the participants affected only the reaction time, not the accuracy.

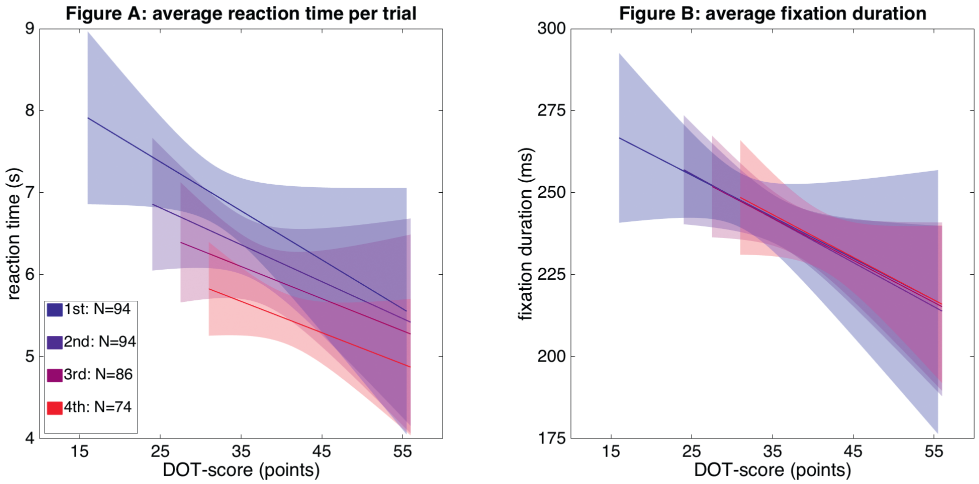

Figure 5.4 – For each yearly repetition, reaction time (Figure A) and fixation duration (Figure B) were both significantly correlated with the DOT score. The reaction time was also significantly affected by the number of repetitions. The shaded areas denote the 95% confidence interval.

To study a possible speed-accuracy trade-off, we analyzed the correlation between reaction times and response accuracies for each yearly repetition. A multiple linear regression was performed to predict the accuracy from the reaction time and the number of repetitions. These variables significantly predicted the accuracy ($r = 441, F(2,345 = 41.591, p < .001$), and both significantly contributed to the model ($\beta_{\text{repetition}} = .423; \beta_{\text{RT}} = .322$; both $p < .001$). Accuracy decreased with decreasing reaction time, and the slope of response accuracy against reaction time was not significantly different for the different repetitions ($slope = 007$,

Table 5.3 – Mean and standard deviation of visual search outcome measures per yearly repetition

Yearly repetition	Age (SD)	Visual search performance		Visual search behavior			
		RT (s) (SD)	Accuracy (fraction correct) (SD)	Fixation Duration (ms) (SD)	No. of Fixations (SD)	Saccade amplitude (degrees) (SD)	Fixation distribution (fraction of fixations on HSF elements) (SD)
1	15.1 (1.6)	6.96 (1.31)	.894 (.059)	252.4 (32.4)	19.81 (3.62)	5.20 (.60)	.744 (.067)
2	16.1 (1.6)	6.32 (1.39)	.906 (.060)	240.8 (29.1)	18.83 (3.91)	5.39 (.63)	.761 (.058)
3	17.0 (1.6)	6.00 (1.34)	.934 (.045)	238.9 (29.0)	17.75 (3.75)	5.54 (.66)	.775 (.065)
4	18.0 (1.6)	5.67 (1.27)	.939 (.042)	236.7 (31.6)	16.72 (3.67)	5.76 (.67)	.784 (.063)

95% $CI = [.003, .011]$, $r = 185$, $p = .001$; comparison between the slopes of the repetitions: $t < 1.237$, $p > .218$).

Visual search behavior

For the outcome measures of search behavior, we found that the DOT score significantly affected the fixation duration, while the number of repetitions significantly affected the number of fixations per trial, the saccade amplitude and the distribution of the fixations over the HSF and LSF elements.

The average *fixation duration* decreased with each repetition, from 252.4 ± 32.4 ms to 236.7 ± 31.6 ms, with an average decrease of 5.054 ms (95% $C = [-7.987, -2.122]$) per repetition (Table 5.3). A multiple linear regression model with the number of repetitions and the DOT score as predictors showed that this decrease was fully mediated by the DOT score (Table 5.2). The contribution of the number of repetitions was not significant. On average, for each one-point increase in the DOT score, the fixation duration decreased by 1.531 ms (95% $CI = [-2.058, -1.004]$). The result was a decrease in the fixation duration with an increase in visuospatial abilities as measured by the DOT, while task repetition did not affect the fixation duration.

The number of repetitions influenced significantly the number of fixations, the saccade amplitude and the distribution of the fixations (Table 5.2). The DOT score had no significant contribution on these outcome measures. The *number of fixations per trial* decreased per repetition from, on average, 19.81 ± 3.62 to 16.72 ± 3.67 (Table 5.3), with an average decrease of .875 (95% *CI* = [-1.274, -.476]) per repetition. The *saccade amplitude* increased with each repetition, from 5.20 ± .60 degrees to 5.76 ± .67 degrees (Table 5.3), an average increase of .182 degrees (95% *CI* = [.113, .250]) per repetition. The fraction of fixations over all trials directed at HSF elements increased on average from .744 ± .067 to .784 ± .063 with each repetition, for an average increase of .012 (95% *CI* = [.005, .019]) per repetition (Table 5.3). Together, these results suggest that visual search behavior becomes more efficient with the annual repetition of the task.

Discussion and conclusions

The present study aimed to investigate, via a longitudinal design, the changes in visual search during the adolescent period and the correlation with changes in visuospatial ability. With interludes of one year, a large group of adolescents participated in the same visuospatial ability task and visual search task. Our results show that both the increase in age and the yearly repetition of the DOT had a positive effect on visuospatial ability. We also observed that visual search accelerated with age because of two different effects. First, the increase in visuospatial ability with age correlates with shorter fixation durations, thus decreasing the reaction time. Second, with repetition of the visual search task, the number of fixations per trial decreases, consequently decreasing reaction time. In addition to the effect of repetition on visual search speed, we found that response accuracy increases with the repetition of the task.

Visuospatial ability, measured by the Design Organization Test (DOT), increased with age. The average increase in DOT score per year corresponds to the findings reported in previous cross-sectional studies (Burggraaf et al., 2015; 2017). One reason why visuospatial abilities increase during childhood might be that visuospatial abilities can increase with, for instance, musical expertise training (Brochard, Dufour, & Després, 2004), certain types of sport (Moreau, Clerc, Mansy-Dannay, & Guerrien, 2012) or video game play (Cherney, 2008; Sanchez, 2012). These activities play an important role during adolescence (Gentile, 2009; Simons, de Vet, Brug, Seidell, & Chinapaw, 2014; North, Hargreaves, & O’Neill, 2000). In addition to a significant effect of age on visuospatial abilities, we found a significant and positive effect of task repetition on the DOT score. Spatial ability has previously been shown to be affected by training (Baenninger & Newcombe, 1989) but, to our knowledge, not by using of the DOT in a longitudinal design. Our results suggest that even over a period of a year, the familiarity with the visuospatial ability task has a positive effect on the performance. Previous studies have shown the DOT to be a viable option for measuring visuospatial abilities relative to tests such as the Block-Design test (Burggraaf, Frens, Hooge, & van der Geest, 2015; 2017; Killgore & Gogel, 2013; Killgore, Glahn, & Casasanto, 2005). Based on our findings, we can conclude that in a longitudinal setup, the DOT is also a viable option; however, when individual development in DOT scores is being assessed, the effect of repetition should be considered.

We found that reaction time and fixation duration decreased with increasing visuospatial abilities during adolescence. These results, together with our findings that visuospatial ability increases with age, confirm the cross-sectional results that reaction times and fixation duration are shorter for older children than for younger children (Burggraaf et al., 2018; Hommel, Li, & Li, 2004; Huurneman & Boonstra, 2015; Seassau & Bucci, 2013). The analysis of our longitudinal visual search data, combined with our results of the visuospatial ability task, shows that this decrease in fixation duration with age can be fully explained by the increase in visuospatial abilities. Thus, an increase in visuospatial abilities makes visual search faster.

Response accuracy did not show a significant correlation with either visuospatial ability or age. This finding supports the results of our cross-sectional study (Burggraaf et al., 2018). However, response accuracy did increase with each repetition of the task. The positive effect of repetition on accuracy has been reported in areas other than visual search, such as reading (Herman, 1985), sports (Benguigui & Ripoll, 1998) and musical performance (Barry, 1992). The effect on accuracy in these different areas, however, was the result of frequent repetitions with short durations in between, while our tasks were performed with interludes of one year. In future research, it might be interesting to investigate the effect of shorter intervals between task repetitions.

The collection of visual information measured in the number of fixations, the saccade amplitude and the distribution of the fixations over the elements with different spatial frequencies, did not change with age. The latter suggests that the efficiency of the processing of visual information from peripheral vision did not change with age. These findings corroborate the findings of our cross-sectional study (Burggraaf et al., 2018) that suggest that the way visual information is collected is already fully matured at the age of twelve. Our present study adds to this that by repetition of the task, this process can still develop further, even at a later age during adolescence. With repetition of the task the number of fixations per trial decreased resulting in an acceleration of visual search. That visual search in adults accelerates has been previously demonstrated, though with extensive training (Newell & Rosenbloom, 1980). Our results add to this that even at intervals of one year visual search accelerates and also response accuracy increases. Next to this increase of response accuracy, we found an increase in accuracy at the saccade level: with repetition a greater fraction of fixations was made on elements with the same spatial frequency as the target. This suggests increased efficiency in the use of information from peripheral vision in order to determine the next fixation location. Thus, our results suggest that repetition of a visual search task can enhance the speed and effectiveness of the process of collecting visual information.

Previous studies have found that the scoring on visuospatial ability tasks is a proxy for intelligence (Hurks, 2013). Thus, it would be interesting to compare the results of the tasks performed in this study with results obtained from children who discontinued their schooling at an early age and children attending schools with a variety of educational levels. Furthermore, one of the results of our longitudinal study is that repetition plays an important part in visual search performance and behavior as well as in visuospatial ability. It might be interesting to further determine the effects of repetition on the outcome measures, for instance, by shortening the intervals between repetitions.

To summarize, the effect of age during adolescence on visual search, which is often reported in cross-sectional studies, can be explained by the increase in visuospatial abilities during adolescence. Our results show that visual search becomes faster with increasing visuospatial ability and more accurate with repetition of the task. Because visual search often forms an important part of many daily tasks, increasing performance in these tasks might positively affect an adolescent's efficiency and effectiveness in these daily tasks. This relationship can prove to be a welcome advantage in a period of life with ever-increasing numbers of tasks to perform and increasing standards of accuracy.

6. General Discussion

The performance and speed with which a visual information is gathered during a search task has often been reported to differ between younger and older adolescents (Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Linn & Petersen, 1985). But since this performance and behavior varies between subjects (Chapter 4), the often used cross-sectional design of these studies hampers the proper assessment of the relationships between them and age. Also, this type of study design makes it difficult to study whether age-related changes in visuospatial skills like visuospatial ability and visuospatial memory (Chapter 2 and 3), might mediate changes in visual search performance and behavior. The general aim of our research was to investigate and quantify in a longitudinal design, the development of performance of and behavior during visual search across adolescence. We also studied correlations between developments in visual search performance and behavior and development in visuospatial ability and visuospatial memory.

Our results using the Design Organization Test (DOT; Burggraaf, Frens, Hooge, & van der Geest, 2015; Killgore & Gogel, 2013; Killgore, Glahn, & Casasanto, 2005) confirmed the increase of visuospatial ability with age found in other studies (Kohs, 1920; Shah & Frith, 1993). The results of our study, though, add to this that repetition of the task also influences the score on visuospatial ability (Chapter 5). This is important to consider when using the DOT in test-retest situations and longitudinal research.

We observed that the visual search task was performed faster when children grew older during the whole period of adolescence (Chapter 5). This corroborates findings of cross-sectional studies that showed that the visual search tasks was performed faster by older adolescents than by younger ones (Chapter 4; Plude, Enns, & Brodeur, 1994; Seassau & Bucci, 2013; Huurneman & Boonstra, 2015; Hoyer, Cerella, & Buchler, 2011; Trick & Enns, 1998; Hommel, Li, & Li, 2004). Our results, though, show that this acceleration with age can be fully explained by the combination of two effects: an increase in visuospatial ability with age and the repetition of the task (Chapter 5). First, the increase in visuospatial ability with age correlated with shorter fixation durations. Searching for the target in our task, participants made multiple fixations and thus a decrease in the duration of each fixation resulted in an acceleration of the search task. Second, with each yearly repetition of the visual search task, the number of fixations per trial decreased which also contributed to the acceleration of the search task. With task repetition, we found that the distance between the fixations increased which might suggest a possible increase of the visual field from which information was extracted during a fixation.

In addition to the effect of task repetition on visual search speed, we found that response accuracy increased with the repetition of the task on trial level as well as on individual fixations level (Chapter 5). The first was reflected in an increase in response accuracy with repetition. The second was reflected in an increase in the efficiency of the selection of fixation locations, i.e. a higher fraction of fixations was directed at elements that were more similar to the target and thus more interesting to examine in details.

For performance on the visuospatial memory task and memory span we saw that the often-reported increase with age (Alloway, Gathercole, & Pickering, 2006; Gathercole, Pickering, Ambridge, & Wearing, 2004) could also be better explained by an increase in visuospatial ability (Chapter 3). We found that the fixation duration was the only outcome measure of visual search that was not affected by the repetition of the task (Chapter 5).

To tentatively explore possible follow-up experiments, we performed two pilot experiments based upon the preliminary results of our experiments that became available during the yearly intervals between the task repetitions. During the first pilot-experiment we administered a shortened version of the visual search task described in this thesis (Chapter 4 and 5) to a group of young children between 7 and 14 years old[1]. A first analysis of the preliminary results suggested that the trends we found in adolescents might already start during childhood. The other pilot-experiment consisted of two tasks that were administered to a group of young adolescents (11-13 years old) and a group of old adolescents (16-18 years old)[2]. The first task was designed to measure the time participants needed to plan a saccade without the need of processing any information. The second task was designed to measure the time needed to process visual information without the need to plan or make saccades. A preliminary analysis of the results hinted that older adolescents, compared with younger adolescents, might processed visual information faster while the time needed to plan a saccade might be the same for both groups. The results of these pilot experiments suggest that it might be interesting to investigate into more detail

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1. These tasks and the results are described in detail in the master-thesis titled 'Development of foveal and peripheral selection in pre-adolescents (7-14 years old)' by Lawrence Stolk, 2016, dept. of applied cognitive psychology, Utrecht University, Utrecht, The Netherlands, available upon request.

2. These tasks and the results are described in detail in the master-thesis titled 'Examining underlying factors in the decrease of fixation duration during adolescence' by Yannick Baak, 2017, dept. of Neuroscience, ErasmusMC, Rotterdam, The Netherlands, available upon request.

the age-related differences in fixation durations during different tasks and also to extend the population-age of the longitudinal study into visual search tasks to children of a pre-adolescence age.

The visuospatial ability task and the visuospatial memory task also suggest possibilities for additional studies. First, a more formal validation of the DOT task aimed at the adolescence age group of all educational levels might be necessary before application in schools. Also the development of a computerized version of for children would make large-scale application more feasible. Additionally the way errors are counted in the DOT might benefit from some further discussion. In the original version of the DOT as well as the version used by us the score is determined by subtracting the number of mistakes from the number of squared filled-in. Though errors are seldom made (Burggraaf, Frens, Hooge, & van der Geest, 2015; Killgore & Gogel, 2013; Killgore, Glahn, & Casasanto, 2005), we found that they are often the result of one systematical error, for instance confusing the number belonging to the black and the white square. This results in multiple of the same errors in the same figure. It might be questioned if all of these errors should be counted or that they should be counted as one and the same error.

Second, due to the time constraint in which the yearly tasks had to be performed, one class-hour of 45 minutes, we were only able to do a cross-sectional study into visuospatial memory together with visuospatial ability and not with visual search. There are indications that visual working memory is correlated to visual search efficiency (Shen, 2011) and search characteristics such as number of refixations (Shen, McIntosh, & Ryan, 2014). The memory task in these studies was not specifically aimed at visuospatial memory, though. In Chapter 3 we described that many different methods exist to distinguish different types of memory. Since visual search within a group of objects has a large locational component, it might be interesting to investigate further the correlation between visual search performance and specifically visuospatial memory.

Throughout the years of research for his thesis, the Design Organization Test has been administered to a very large group of adolescents. The increase of the DOT score with the level of education within the school is a strong indication that, like with other visuospatial ability tests (Hurks, 2013), the DOT-score might be a strong indication of the intellectual level of adolescents. Together with the ease of administration and the fact that the test can be administered group wise make it an interesting test to give schoolchildren yearly to get a quick indication of their intellectual development. Also it might be indicative in the process of choosing the right school. The DOT is a quick and easy to administer test but when used in a longitudinal study or in a test-retest experimental set-up, care should be taken that the score should be corrected for task repetition.

The fixation duration that can be determined by the visual search task is strongly correlated with the DOT-score. The visual search task is a more laborious one but has the advantage that fixation duration, unlike the DOT-score, is not affected by task repetition. Another advantage of the visual search task is that it can also be used if the aim is to study the effect of the repetition of a task. Outcome measures like the average number of fixations per trial and the saccade amplitude were not affected by age nor visuospatial ability and just by task repetition. To summarize, the visual search task is a more laborious task than the DOT, but provides a broader scope of outcome measures that differ in the way they are affected by age, visuospatial ability and / or task repetition.

Visual search forms an important part of many daily tasks and our results suggest that visual search performance can increase with increasing visuospatial ability thus possibly having advantageous effects throughout the day. This visuospatial ability can be increased in various ways, for instance by playing sports and learning to make music. Thus we can tentatively suggest that for a child's development during adolescence, it is important that children are challenged to partake in these kinds of activities. This might prove to be a welcome advantage in a period of life with an ever-increasing numbers of tasks and responsibilities that society puts on their shoulders.

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8. Summary

The aim of this thesis is to investigate developments in visual search behavior during adolescence, using a longitudinal design. We also study the correlations between visual search behavior and other visuospatial characteristics such as visuospatial ability and visuospatial memory.

Chapter 2 describes a cross-sectional study of the difference in visuospatial ability between children of different ages during adolescence. This research was carried out using the Design Organization Test (DOT). From the results of this test it follows that the visuospatial ability of older children is greater than that of younger children. The advantage of the DOT above, for example, the Block Design Test, is that it lasts only 10 minutes (including explanation) and can also be administered in groups and by the use of just pen and paper.

Chapter 3 deals with the cross-sectional research in which the differences in visuospatial memory capacity are studied between adolescents of different ages. In addition, this research describes the correlation of visuospatial memory and visuospatial ability. The results show that the visuospatial memory capacity of older children is greater than that of younger children. This research also shows that the correlation of the memory capacity with the visuospatial ability is stronger than that with age.

Chapter 4 gives a detailed description of the differences in visual search behavior and in visual search performance of adolescents between 12 and 19 years old. In addition to describing the effect of age, also the influence of different spatial frequency and orientation of the objects on visual search behavior is described. The results of this study show that older children search faster than young children without performing less accurate. Other characteristics of the search behavior, for example the number of fixations per search display and the selection of potentially interesting elements to fixate, do not appear to differ for the different age groups. Characteristics such as spatial frequency and orientation appear to have an equally large influence on the fixation time and the selection of elements to fixate for younger and older children.

Chapter 5 describes the design and results of a longitudinal study of visual search behavior, visual search performance and visuospatial ability of adolescents. For this study, a large group of adolescents performed the same visual search task and visuospatial ability task during four annual sessions. The results show that the changes during adolescence in visual search behavior can be fully described by the increasing visuospatial ability during adolescence. The results also show that search behavior becomes more efficient with the repetition of the search task.

Chapter 6 summarizes the different results and discusses suggestions for further research, based, among other things, on two pilot experiments carried out in recent years.

9. Samenvatting

Het doel van deze thesis is om, met behulp van een longitudinale opzet, de ontwikkelingen te onderzoeken in visueel zoekgedrag tijdens de adolescentie. Tevens bestuderen we de correlaties tussen visueel zoekgedrag en andere visuospatiele karakteristieken zoals visuospatiele vaardigheid en visuospatieel geheugen.

Hoofdstuk 2 beschrijft een cross-sectioneel onderzoek naar het verschil in visuospatiele vaardigheid tussen kinderen van verschillende leeftijden tijdens de adolescentie. Dit onderzoek werd uitgevoerd met behulp van de Design Organisation Test (DOT) gebruikt. Uit de resultaten van deze test volgt dat de visuospatiele vaardigheid van oudere kinderen groter is dan van jongere kinderen. Het voordeel van de DOT boven, bijvoorbeeld, de Block Design Test, is dat hij slechts 10 minuten duurt (inclusief uitleg) en ook groepsgewijs afgenomen kan worden en met behulp van slechts pen en papier.

Hoofdstuk 3 behandelt het cross-sectionele onderzoek waarin de verschillen in visuospatieel geheugen bestudeerd worden tussen adolescenten van verschillende leeftijden. Tevens wordt in dat onderzoek de correlatie beschreven van visuospatieel geheugen en visuospatiele vaardigheid. Uit de resultaten blijkt dat de visuospatiele geheugencapaciteit van oudere kinderen groter is dan van jongere kinderen. Tevens blijkt uit dit onderzoek dat de correlatie van de geheugencapaciteit met de visuospatiele vaardigheid sterker is dan die met de leeftijd.

Hoofdstuk 4 geeft een uitgebreide beschrijving van de verschillen in visueel zoekgedrag en in de visuele zoekprestaties van adolescenten tussen de 12 en 19 jaar oud. Naast het beschrijven van het effect van leeftijd, wordt ook de invloed van verschillende spatiele frequenties en oriëntaties van de objecten op visueel zoekgedrag beschreven. De resultaten van dit onderzoek laten zien dat oudere kinderen sneller zoeken dan jongeren zonder onnauwkeuriger te worden. Andere karakteristieken van het zoekgedrag, bijvoorbeeld het aantal fixaties per plaatje en de selectie van mogelijk interessante elementen om te fixeren, blijken niet te verschillen voor de verschillende leeftijdsgroepen. Karakteristieken als spatiele frequentie en oriëntatie blijken voor jongere en oudere kinderen een even grote invloed te hebben op de fixatieduur en de gemaakte selectie van elementen om te fixeren.

Hoofdstuk 5 beschrijft de opzet en de resultaten van een longitudinaal onderzoek naar het visuele zoekgedrag, de visuele zoekprestatie en de visuospatiele vaardigheid van adolescenten. Voor dit onderzoek verrichtte een grote groep adolescenten gedurende vier jaarlijkse sessies dezelfde visuele zoektaak en visuospatiele vaardigheid taak. De resultaten laten zien dat de veranderingen tijdens de adolescentie in visueel zoekgedrag geheel beschreven kunnen worden door de toenemende visuospatiele vaardigheid in die leeftijdscategorie. De resultaten beschrijven tevens dat het zoekgedrag efficiënter wordt met de herhaling van de zoektaak.

Hoofdstuk 6 geeft een samenvatting van de verschillende resultaten en behandeld suggesties voor verder onderzoek, onder andere gebaseerd op twee pilot-experimenten die in de afgelopen jaren werden uitgevoerd.

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Publications

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Presentations and poster-presentations:

2018 Helmholtz retreat *(final results of longitudinal study of visual search and visuospatial abilities)*

2017 Society for Neuroscience *(poster; first results of longitudinal study of visual search)*

2016 Neuroscience meeting Erasmus MC *(results of study of visuospatial memory and ability)*

2015 ECEM, Vienna, Austria *(results of cross-sectional study of visual search)*
Colloquium Experimental Psychology, Utrecht University *(results of cross-sectional study of visual search)*

2014 Helmholtz retreat *(results of development of visuospatial ability)*
Universidad Mayor de San Andrés (UMSA), La Paz, Bolivia *(possibilities of eye-tracking research in general and visual search in specific)*
Universidade de São Paulo (USP), São Paulo, Brazil *(possibilities of eye-tracking research in general and visual search in specific)*

2012 ENP *(poster; results of pilot study)*
Helmholtz retreat *(results of pilot study)*

2011 Helmholtz PhD day *(study-design)*
NWO *(study-design)*

Curriculum Vitae

Rudolf Burggraaf werd op 3 september 1968 geboren in Steenwijk, is getrouwd met Marc Wingens en heeft drie kinderen en inmiddels vijf kleinkinderen. Na het behalen van het VWO diploma op het Lambert Franckens College in Elburg, ging hij in 1986 natuurkunde studeren aan de Universiteit Utrecht. In het laatste jaar van zijn studie deed hij onderzoek bij de vakgroep van prof. dr. J. J. Koenderink, medische- en fysiologische fysica. Daar deed hij onderzoek naar de temporele verschillen in de verwering van visuele informatie met verschillende spatiele frequenties.

Na het behalen van zijn doctoraal diploma, een jaar reizen en ruim een jaar zijn dienstplicht vervullen, is hij een onderwijs instituut gestart gericht op het individueel ondersteunen van leerlingen in exacte vakken. Na een aantal jaren heeft hij klassikaal lesgeven toegevoegd aan zijn onderwijservaringen door wis- en natuurkunde lessen te verzorgen aan het Christelijk Gymnasium Utrecht. Tegelijkertijd had hij stichting Happy Days opgericht die zich richtte op het faciliteren van de zelfstandige ontwikkeling van schoenpoetsende straatkinderen in La Paz, Bolivia. Het werk voor de stichting nam steeds meer tijd in beslag en in 2003 stopte hij met werken om zich voltijds te kunnen richting op het werk in Bolivia. In een later stadium heeft hij daar ook projecten in de sloppenwijken van São Paulo, Brazilië aan toegevoegd. Daar was zijn werk gericht op het bouwen van een ziekenhuis en een school. Parallel daar aan heeft hij de stichting Solid House Foundation opgericht. Deze had als doel het mogelijk maken dat mensen zelf leren op een eenvoudige manier koepelhuizen te bouwen. Naast in Bolivia zijn, onder begeleiding van deze stichting, kleine en grote wijken met deze huizen gebouwd in vele landen op meerdere continenten.

Nadat de meeste projecten naar tevredenheid van de deelnemers waren afgesloten is hij terug gekomen naar Nederland. Hij is daar begonnen om op het Gemeentelijk Gymnasium van Hilversum een vernieuwingsslag te maken bij de sectie natuurkunde alsmede te werken aan het verbinden van de school aan bèta-gerelateerde netwerken en Europese netwerken. Na een aantal jaren van meer lesgericht- en organisatorisch gericht bezig te zijn geweest kwam de wens op om zich weer een aantal jaren vakinhoudelijk te verdiepen. Aansluitend bij zijn onderzoek aan het einde van zijn natuurkundestudie kreeg hij de gelegenheid om een onderzoek te gaan doen bij de afdeling neurowetenschappen aan het Erasmus MC. Ondersteund door een beurs van het NWO en gefaciliteerd door de schoolleiding heeft hij gedurende 5 jaar twee dagen in de week kunnen werken aan het onderzoek waar deze thesis de afsluiting van is. Dit onderzoek was een prachtige gelegenheid om zijn fascinatie voor neurowetenschappen samen te brengen met zijn vertrouwdheid om met adolescenten te werken. Een volgende stap zal hopelijk deze twee elementen in zich dragen samengevoegd met zijn organisatorische ervaringen en zijn ervaringen met de cultuur en de talen in Zuid-Amerika.

Interview over promotiebeurs voor docenten

VOION (Voortgezet Onderwijs in Ontwikkeling), februari 2015

"Het heeft me een betere docent gemaakt"

Werken in het voortgezet onderwijs betekent blijven werken aan je persoonlijke ontwikkeling. Ieder doet dat op zijn eigen manier. Neem Rudolf Burggraaf. Hij doet – naast zijn werk als docent natuurkunde – promotieonderzoek aan de Erasmus Medisch Centrum Rotterdam. Daarbij krijgt hij ondersteuning van een promotiebeurs. "Ik moet er heel wat voor laten, maar krijg er ook veel voor terug."

Na zijn studie Medische Natuurkunde en een carrière in het ontwikkelingswerk in Bolivia en Brazilië ging Rudolf Burggraaf zes jaar geleden van start als docent natuurkunde aan het Gemeentelijk Gymnasium Hilversum. Een mooie uitdaging. Maar na een paar jaar begon het te kriebelen. "Ik had de universitaire wereld na mijn afstuderen vaarwel gezegd en dacht dat promoveren er niet meer inzat. Toch begon ik daar steeds meer aan te twijfelen. Ik ging bijvoorbeeld met leerlingen op excursie naar het CERN in Zwitserland en zag daar al die onderzoekers rondlopen. Dat wilde ik ook! Maar ik bleef beren op de weg zien."

Wat heeft je uiteindelijk dan toch over de streep getrokken?

"Uiteindelijk heeft een oud-studiegenoot mij op het juiste spoor gezet. Hij zei dat ik het naast mijn werk moest uitproberen. Gewoon klein beginnen met het ophalen van wat theorie en vervolgens kijken of ik niet een eigen onderzoekje kon opzetten. Zo gezegd, zo gedaan. Ik vond het zo leuk dat ik serieus een carrièreswitch overwoog. Totdat ik in de lerarenkamer op school een foldertje zag liggen over de promotiebeurs. Hiermee kunnen leraren die promotieonderzoek doen voor veertig procent van hun aanstellingsomvang studieverlof krijgen. De school krijgt subsidie om vervanging te regelen. De promotiebeurs was voor mij de ideale oplossing. Ik hoefde het onderwijs niet vaarwel te zeggen, maar kon mezelf wel verder ontwikkelen."

Hoe heb je het vervolgens aangepakt?

"Eerst heb ik op school met onze directeur overlegd. Die moest er wel achterstaan; hij moet per slot van rekening gedurende vier jaar voor twee dagen in de week een vervanger voor mij regelen. Gelukkig was hij meteen enthousiast. Het past ook gewoon goed in het plaatje van de school. Het Gemeentelijk Gymnasium legt veel nadruk op de persoonlijke ontwikkeling van docenten. Bovendien willen we dat leerlingen bij ons op school een onderzoeksgerichte houding ontwikkelen. De verwachting was bovendien dat ik de school met mijn promotieonderzoek ook veel terug zou kunnen geven. Gelukkig werd mijn aanvraag goedgekeurd en kon ik in augustus 2012 met een lerarenbeurs aan mijn onderzoek beginnen.”

We zijn inmiddels meer dan drie jaar verder. Wat heeft je promotieonderzoek je gebracht?

“Ik vind het fantastisch dat ik het doen van onderzoek kan combineren met in het voortgezet onderwijs. Het heeft me een betere docent gemaakt. Ik ben bijvoorbeeld begripvoller geworden. Doordat ik zelf ervaar hoe moeilijk het is om goed onderzoek te doen, weet ik dat we heel wat van onze leerlingen vragen. Daarom probeer ik hen goed te helpen tijdens practica of met het onderzoek dat ze voor hun profielwerkstuk moeten doen. Niet door het voor te doen, maar door vragen te stellen en kritisch te zijn. Ook heb ik ingezien hoe belangrijk het is om goed samen te werken met collega’s, ook buiten mijn eigen vakgroep. Het is een cliché, maar twee weten toch echt meer dan één. Toch vind ik de combinatie van promotieonderzoek en lesgeven behoorlijk zwaar. Het slurpt gewoon al mijn tijd op. Zo is vakantie voor mij niet echt vakantie. Dan wil ik namelijk meters maken met mijn onderzoek.”

Wat motiveert je om er toch voor te blijven gaan?

“Hoewel ik er heel wat voor moet laten, krijg ik er ook veel voor terug. Het is gewoon ontzettend leuk om wetenschappelijk onderzoek te doen, om mijn horizon te verbreden. Positief is ook dat mijn onderzoek goed heeft uitgepakt. Zo is onlangs mijn eerste artikel in een wetenschappelijk tijdschrift verschenen en is een tweede artikel in de maak. Dat is voor mij de kers op de taart, en een enorme motivatie om ermee door te gaan.”

Dankwoord: En zij zeiden allemaal: “ja”

In volgorde van opkomst:

Ignace Hooge: Jij zei zonder terughoudendheid ‘ja’ toen ik heel voorzichtig eens opperde tijdens een oud-en-nieuw feest of jij dacht dat er ergens wel een mogelijkheid voor mij zou zijn om een promotietraject te volgen. En je stelde jezelf ook meteen beschikbaar als co-promotor, wat een vertrouwen!

Maarten Frens: jij zei ‘ja’ toen ik jou, via tussenkomst van Ignace, vroeg of jij het zou zien zitten om mijn promotor te worden. De zorg waarmee je mij, mijn onderzoek en de andere promovendi op je afdeling begeleidt is, weet ik nu, exceptioneel. Ik weet nu dat vrijwel alle promovendi jaloers zijn op mij met zo’n betrokken promotor.

Sjoerd van de Berg , Hans Crum en Carolien Barkey Wolf: jullie zeiden, als schoolleiders van het Gemeentelijk Gymnasium in Hilversum, zonder een moment van twijfel ‘ja’ toen ik jullie vroeg of ik twee dagen per week vrijgesteld kon worden van lesgeven om mijn promotieonderzoek te gaan doen ongeacht alle organisatorische uitdagingen die het voor jullie meebracht. Jullie hebben mij daarmee de ruimte en tijd gegeven om mij op een bijzondere manier te ontwikkelen.

Jos van der Geest: lieve Jos, wat een groot geluk voor mij dat jij ‘ja’ zei toen ik je, op het moment dat alles duister was, vroeg om mij dagelijks te gaan begeleiden tijdens het proces van het schrijven. Door je geduld, toewijding, steun en medeleven en de broodnodige afleiding in de vorm van koffie met koekjes en lunch met patat (de beste van Rotterdam) en Surinaamse broodjes, kreeg ik weer zin en plezier in het werk.

Marc Wingens-Burggraaf: jij zei het belangrijkste ‘ja’ dat ik ooit gehoord heb, namelijk toen ik je vroeg met mij te trouwen. Alleen door jouw niet aflatende steun, luisterend oor, lieve aaien over mijn bol en schouderklopjes (op mijn rechterschouder) heb ik het af kunnen maken. Wat heerlijk dat ik, nu het afgerond is, samen met jou kan gaan genieten van het vervolg van dit grote project, welk vervolg dan ook.

Alena, Alexander, Aline, Anne ,Arjen, Bas, Bram, Cedrine, Charlotte, Cile, Cloë, Coen, Costijn, Daan, Danja, David, Derek, Eric, Erik, Ernesto, Ethan, Etienne, Finn, Fleur, Floor, Floor, Floor, Gemma, Gerhard, Hannah, Ilse, Imke, Iris, Isabeau, Jamil, Jan, Jasper, Jesse, Jesse, Jip, Jonathan, Joost, Josephine, Joyce, Judith, June, Jurre, Koen, Koen, Lars, Laura, Laurens, Lideweij, Lisanne, Lotte, Luc, Maiwand, Marc, Marijn, Marlinde, Marloes, Martijn, Matt, Maurice, Max, Maximiliaan, Meeuwes, Nora, Nynke, Ole, Paul, Pieter, Pieter, Pieter, Pieter, Reinier, Reno, Rosalie, Sebastian, Sophie, Steven, Stijn, Susanna, Tamara, Tessa, Thijs, Thijs, Thomas, Thomas, Ties, Veerle, Veerle, Vincent, Vincent, Vincent, Wessel, Willem, Wouter, Wouter, Xavier, Yasmin: Jullie zeiden allemaal 'ja' toen ik in de klas kwam vragen of er mensen waren die mee wilden doen met een wetenschappelijk onderzoek. Zelfs toen jullie wisten hoe zwaar de experimenten waren hebben jullie je jaar-in, jaar-uit ingezet om dit onderzoek mogelijk te maken. Elk jaar weer driekwartier lang kijken naar rondjes met streepjes… wat een doorzettingsvermogen. Op de momenten dat ik het onderzoek het moeilijkst vond heeft het contact met jullie mij altijd weer de energie gegeven om door te gaan.

En dan zijn er nog twee mensen die buiten alle tijd en ruimte staan.

Jos en Wouter: Voor jullie was niets zo vanzelfsprekend dan dat jullie je om mijn zielenheil zouden bekommeren tijdens deze lange, lange reis met struikelblokken en duwen op mijn hart. Wie zou kunnen vermoeden dat het slagen van een wetenschappelijk onderzoek afhangt van 'port in bad' en 'koffie op vrijdagochtend'. Met jullie constante zorg is dit grootse werk begonnen, uitgevoerd en afgerond, en daarvoor verkrijgen jullie van mij oneindige roem en eeuwige dankbaarheid.

Samen met mijn familie, mijn vrienden en mijn broeders, vormden jullie mijn persoonlijke leger beschermengelen. Ik ben dankbaar voor de niet aflatende steun die iedereen mij heeft gegeven tijdens de afgelopen jaren. Ik was gerust dat ik met jullie aan mijn zijde heb kunnen rouwen om het verlies van mijn vader en dat ik met jullie aan mijn zijde mijn huwelijk heb kunnen vieren, de belangrijke momenten van mijn leven die zich afspeelden tegen achtergrond van dit promotieproces.

Liefs,
Rudolf