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

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ABSTRACT

Using a longitudinal study design, a group of 94 adolescents participated in a visual search task and a visuospatial ability task yearly for four consecutive years. 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 different types of elements. We found that both the increase in age and the yearly repetition of the DOT had a positive effect on visuospatial ability. We show that the acceleration of visual search during childhood can be explained by the increase in visuospatial abilities with age during adolescence. With the yearly task repetition, visual search became faster and more accurate, while fewer fixations were made with larger saccade amplitudes. The combination of increasing visuospatial ability and task repetition makes visual search more effective and might increase the performance of many daily tasks during adolescence.

KEYWORDS

Adolescence; design organization test; development; fixation duration; foveal discrimination; longitudinal; peripheral selection; saccade selection; visual search; visuospatial ability

Introduction

From infancy to young adulthood, children develop and improve upon many different abilities, including social cognition, organization, decision making, and planning (Blakemore, 2008; Crone 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 accurately as possible whether a certain target is present in a display. Visual search can easily be studied in a laboratory environment wherein performance and behavior can be assessed. Search performance relates to the result of the search, based on how quickly and accurately a target's absence or presence is determined. Search behavior describes the manner in which a search is executed, such as determining which objects are selected for visual inspection and how long they are fixated upon.

Visual search performance and behavior change with age. In a previous study, using a cross-sectional design with adolescents aged 11 to 20 years, we observed that search became faster with age (shorter fixation and reaction times), while accuracy remained the same (Burggraaf, van der Geest, Frens, & Hooge, 2018). Visual search times already start decreasing at preadolescence and subsequently increase during late adulthood (Hoyer et al., 2011; Plude & Hoyer, 1986; Plude et al., 1994; Trick & Enns, 1998). The decrease in visual search times is largely a result of shorter fixation durations, while the number of fixations does

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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 lies 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 with changes in age but do not take into account the fact that age-related changes in other visually related abilities, such as visuospatial ability. Visuospatial ability encompasses pattern recognition and part-to-whole integration. These are abilities that are also instrumental to our visual search task (Burnett Heyes, Zokaei, van der Staaij, Bays, & Husain, 2012; Linn & Petersen, 1985) For example, the analysis of the pattern of the focused element is necessary to determine whether it is the target or not while the part-to-whole integration of the visual search display can be used to determine in which direction the next saccade shall be made. Visuospatial ability 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 among subjects, thereby hampering the proper assessment of relationships among 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 a visuospatial ability task in a single experimental session. These experimental sessions were repeated over four consecutive years at 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 increases 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 shared visual characteristics with the target to a greater or lesser extent. 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 at which 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 formed a subgroup of the population reported on 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, for a maximum of four times, resulting in between 1 and 4 repetitions.

Visual search task

To analyze visual search performance and behavior, we chose to use an ecologically valid task representing eye movements during visual search in daily life situations. Because previous studies showed an age effect on the speed of identification processing of visual information only when the task was sufficiently difficult, we opted for a conjunction task, with Gabor patches as elements to have different types of distractors, varying from the target in two ways: spatial frequency and orientation. To stimulate participants to look at all, or most, of the elements in the visual search display, we inserted 50% target-absent trials. This setup and procedure were the same as those used in our previous cross-sectional study and are summarized in the following sections (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 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.

In 72 of the 144 search displays, we used mixed-frequency displays (Figure 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/° and had different orientations than the target. All nontargets were randomly placed over the 36 possible locations. The other half of the trials used single-frequency displays, with all nontargets 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 three additional repetitions.

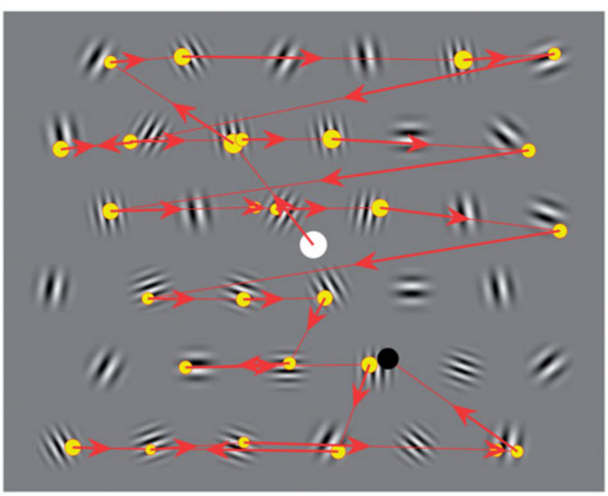

Figure 1. Example of a mixed-frequency display with the target present. All elements have been enlarged for visibility. The target is the third element from the right in the second row from the bottom. The element on the top-left of the display is a low spatial frequency (LSF) element, and the element on the bottom-left of the display is a high spatial frequency (HSF) element. The orientation of each nontarget 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 depicts the location of the first fixation, while the black dot depicts the final location, and the yellow dots show the intermediate fixations. The radius of the dot 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.

The participants received verbal instructions regarding the task details, various stimulus elements, and 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 the 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 correct responses. 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, as the saccade amplitude might be an indication of the size of the area for which the visual system can analyze information during a fixation. Additionally, we determined the average fixation duration per trial, which we used 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 were 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. 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 a slightly shorter variation of the Design Organization Test (DOT; Killgore et al., 2005; Killgore & Gogel, 2014). Our own previous research (Burggraaf et al., 2015, 2017) showed the usability of a slightly shorter variation of the DOT instead of the Block-Design test when determining the development of visuospatial ability during adolescence. An advantage of the DOT is that it takes only approximately 10 minutes to explain and administer, which is much faster than the Block-Design test. As stated in the participants section, all tasks had to be performed within a school hour, which lasted only 45 minutes; therefore, we chose the DOT to measure the development of visuospatial ability.

The DOT consists of two test forms and a practice form (Figure 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.

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, 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 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,

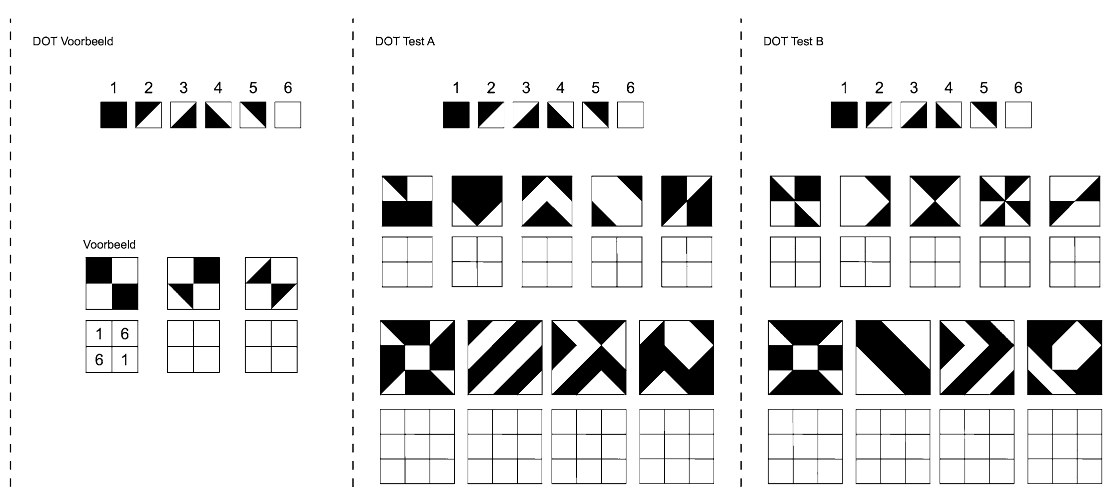

Figure 2. The Design Organization Test (DOT) consists of a practice form labeled "DOT Voorbeeld" (which is Dutch for "DOT example") and two forms labeled "DOT Test A" and "DOT Test B." At the top of each form, each pattern is combined with a specific numerical code.

all data from participants who ended the visual search task prematurely were discarded.

For analysis of the visuospatial ability task, a linear regression model was used. One of the independent variables was the number of yearly repetitions, which could vary between 1 and 4, with 1 corresponding to the first participation time and 4 corresponding to the maximum of four times the tasks were performed. All repetitions were performed approximately 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) made 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 among 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 linear regression, the slope and 95% confidence interval. The threshold for significance was set to an alpha level of .05.

Results

A total of 94 participants (55 males; Table 1) successfully completed the experiment for at least two consecutive years; 86 (49 males) completed the experiment for three consecutive years, and 74 (42 males) successfully completed the experiment for four consecutive years.

Visuospatial ability

We measured visuospatial ability with the DOT. The individual scores on this test varied between 16.0 and 56.0 points. The average DOT scores increased with each yearly repetition (32.0 ± 5.7, 36.0 ± 5.8, 37.6 ± 5.7, and 40.3 ± 6.2, respectively). Multiple linear regression analysis was performed to predict the DOT score from the number of repetitions and age (Figure 3). 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.

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,

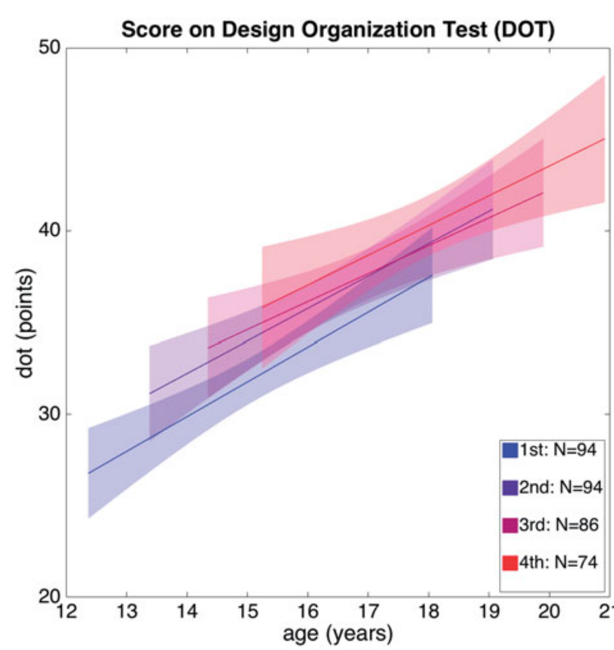

Figure 3. Score on the Design Organization Test (DOT) versus age for each yearly repetition. The shaded areas denote the 95% confidence interval.

Table 1. Description of the populations 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)

Table 2. Comparison of the full model (predictors: number of repetitions, DOT score, and age) with the reduced model (predictors: number of repetitions and DOT score) in predicting the value of the outcome measures.

	$r_{full\ model}$	$r_{reduced\ model}$ (F(2,345), $p < .001$)	$\beta_{DOT\text{-}score}$	$\beta_{repetition}$
Reaction time	.388	.387 (F = 30.338)	**−.236, $p < .001$**	**−.218, $p < .001$**
Accuracy	.320	.319 (F = 19.535)	−.016, $p = .776$	**.326, $p < .001$**
Fixation duration	.342	.340 (F = 22.594)	**−.323, $p < .001$**	−.035, $p = .540$
No. of fixations	.314	.306 (F = 17.844)	−.101, $p = .078$	**−.247, $p < .001$**
Saccade amplitude	.301	.300 (F = 17.006)	−.001, $p = .984$	**.300, $p < .001$**
Fixation distribution	.234	.232 (F = 9.781)	.049, $p = .407$	**.206, $p < .001$**

Note. In the full model, age did not contribute significantly to any of the outcome measures.
Bolded values are significant at .05.

average amplitude of saccades and fraction of fixations made on HSF elements. Using age alone as a predictor, all outcome measures were significantly correlated with age. As discussed in the visuospatial ability section, age was strongly and positively correlated with the DOT score. We analyzed whether the number of repetitions and the DOT score mediated the correlation between age and outcome measures. To this end, we performed multiple regression analysis using age, the number of repetitions and the DOT score as predictors (Table 2, full model). At this point it is important to note that since repetition of the experiment was approximately with increments of one year, the "increment of age" and "the increment of repetition" are very strongly correlated, but "age" and "repetition" themselves are not. For instance during the first year, repetition = 0 for all participants while their age varied between 12.4 and 18.1 years old. Therefore, neither of them was a-priori redundant. Specifically, in our model, age appeared not to be a significant contributor to any of the outcome measures while repetition was a significant contributor to, for instance, the response accuracy. The effect of age was mediated by the DOT score (for the fixation duration), the number of repetitions (for the response accuracy, number of fixations per trial, saccade amplitude, and 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 not using age as a predictor (Table 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 or both were significant contributors to the model.

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 2). The average reaction time decreased with each repetition, from 6.96 ± 1.31 s to 5.67 ± 1.27 s (Table 3), decreasing on average by .285 s (95% CI [−.428, −.143]) per repetition. Furthermore, the average reaction time decreased by .052 s (95% CI [−.076, −.028]) with each one-point increase in the DOT score (Figure 4A). Multiple linear regression analysis 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 2). The average response accuracy increased from .894 ± .059 to .939 ± .042 (Table **3**), increasing on average by .016 (95% CI [.011, .021]) per repetition. 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.

To study a possible speed-accuracy tradeoff, we analyzed the correlation between reaction times and response accuracies for each yearly repetition. Multiple linear regression analysis was performed to predict the accuracy from the reaction time and 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 ($\beta_{repetition} = .423$; $\beta_{RT} = .322$; both $p < .001$). The accuracy decreased with decreasing reaction time, and the slope of the response accuracy against reaction time was not significantly different for the different repetitions (slope = .007, 95% CI = [.003, .011], $r = .185$, $p = .001$; comparison of the slopes of the repetitions: $t < 1.237$, $p > .218$).

Visual search behavior

For the outcome measures of search behavior, the DOT score significantly affected the fixation duration, while the number of repetitions significantly affected the number of fixations per trial, the saccade

Table 3. Mean and standard deviation of visual search outcome measures per yearly repetition.

		Visual search performance		Visual search behavior			
Yearly repetition	Age (*SD*)	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)

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% CI [−7.987, −2.122]) per repetition (Table 3). A multiple linear regression model with the number of repetitions and DOT score as predictors showed that this decrease was fully mediated by the DOT score (Table 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 significantly influenced the number of fixations, the saccade amplitude and the distribution of fixations (Table 2). The DOT score did not significantly contribute to 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 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 3), with 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 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, changes in visual search during the adolescent period and their correlation with changes in visuospatial ability. At 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. Oculomotor control of fixations is fully developed before adolescence (Aring, Grönlund,

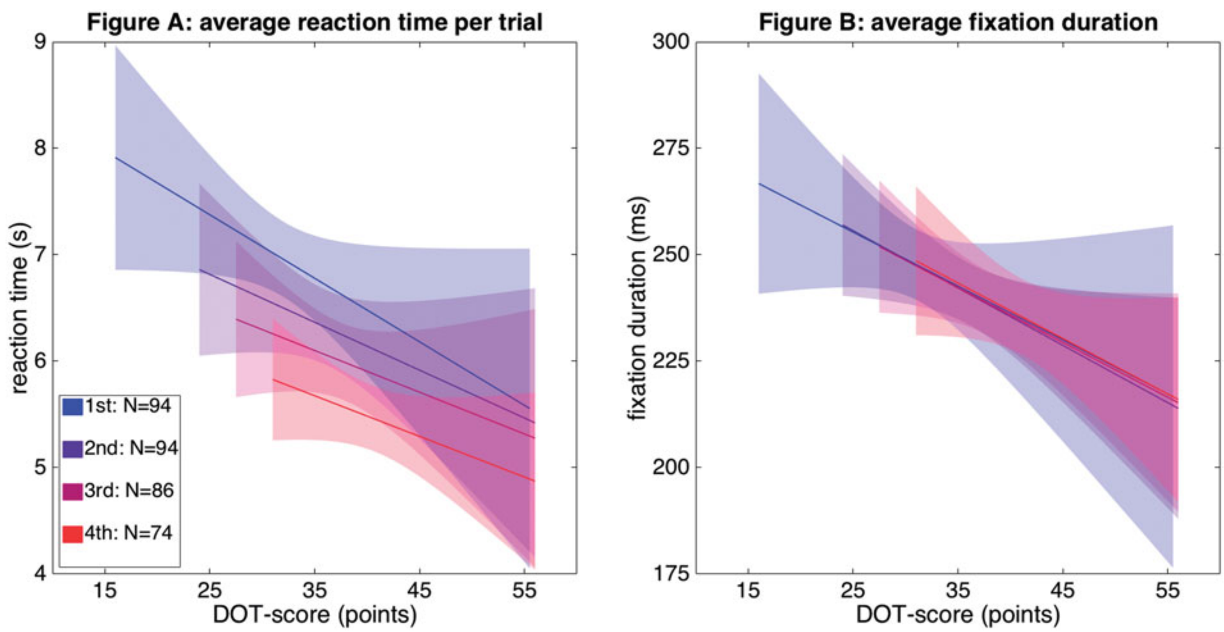

Figure 4. For each yearly repetition, reaction time (Figure A) and fixation duration (Figure B) were both significantly correlated with the DOT score. The reaction time was also significantly affected by the number of repetitions. The shaded areas denote the 95% confidence interval.

Hellström, & Ygge, 2007), suggesting that the ongoing development of search strategy and cognitive abilities rather than the development of oculomotor control underlies our findings in adolescents. 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 DOT, increases with age. The average increase in the 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 sports (Moreau, Clerc, Mansy-Dannay, & Guerrien, 2012), or video game play (Cherney, 2008; Sanchez, 2012). These activities play an important role during adolescence (Gentile, 2009; North, Hargreaves, & O'Neill, 2000; Simons, de Vet, Brug, Seidell, & Chinapaw, 2014). 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 use of the DOT in a longitudinal design. Our results suggest that even over a period of one year, familiarity with the visuospatial ability task has a positive effect on performance. Previous studies have shown the DOT to be a viable option for measuring visuospatial abilities relative to some tests, such as the Block-Design test (Burggraaf et al., 2015, 2017; Killgore & Gogel, 2014; 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 is being assessed with DOT scores, the effect of repetition should be considered.

We found that the 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). Analysis of our longitudinal visual search data combined with our results of the visuospatial ability task show that this decrease in fixation duration with age can be explained by the increase in visuospatial abilities. Thus, an increase in visuospatial abilities increases the speed of visual search.

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 increased 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 at 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 fixations over the elements with different spatial frequencies did not change with age. The latter result suggests that the efficiency of processing visual information from peripheral vision did not change with age. These findings corroborate the findings of our cross-sectional study (Burggraaf et al., 2018) suggesting that the manner in which visual information is collected is fully mature at the age of twelve. The distance used between the elements of approximately 4° may have restricted the saccade amplitudes of the participants. However, participants exhibited a wide array of saccade amplitudes, signifying that they did not limit their saccades to elements located only immediately adjacent to the focused element but made saccades over the whole visual search display (viewing field: 26.4° × 21.4°). Therefore, we believe that the effect of this constraint is limited. Our present study supports the idea that the manner in which visual information is collected can develop even further by repetition of the task, 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. Accelerating visual search in adults has been previously demonstrated, though with extensive training (Newell & Rosenbloom, 1980). Our results add to this finding that even at intervals of one year, visual search accelerates, and response accuracy increases. Next, to further corroborate this increase in 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, suggesting increased efficiency in the use of information from peripheral vision 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.

A limitation of our study is that the participants were all students who achieved high scores on a national intelligence test. Since previous studies have found that scoring on visuospatial ability tasks is a proxy for intelligence (Hurks, 2013), further studies are needed to investigate the generalizability of our results. For instance, 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 from children attending schools with a variety of educational levels. Furthermore, our longitudinal study demonstrated that repetition plays an important role 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. In the present study, no a priori hypotheses were generated involving sex differences since this was outside the aim of the study. However, we performed post hoc analyses concerning possible sex differences within the results of the tasks. These analyses showed no significant difference between male and female participants in any of the outcome measures. Sex differences in visuospatial ability have previously been shown to be small (Weiss, Kemmler, Deisenhammer, Fleischhacker, & Delazer, 2003) and only present when the task involves mental rotation (Linn & Petersen, 1985). The absence of mental rotation in our visuospatial- and visual search tasks, in combination with the reported correlation between the results of the two tasks could explain the equal performance of both sexes.

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 to complete these daily tasks. This relationship may be a welcome advantage in a period of life in which an ever-increasing number of tasks must be performed with increasing standards of accuracy.

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