Visual search accelerates during adolescence

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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 ($N = 140$; age: 12–19 years; 47% female, 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. Nontargets 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.

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 subtasks 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 subtask is based on information gained from foveal vision and addresses whether the element in focus is the target. Sensory-detection thresholds place

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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 5 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.

In addition to the aforementioned sensory factors, adequately performing a visual search involves various skills, such as object recognition, decision making, and planning, that relate to one or both subtasks. 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 early adulthood (Casey, Tottenham, Liston, & Durston, 2005; Crone, 2009; 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 (Hommel et al., 2004) has reported a significant decrease in response accuracy as age increased from childhood (6 years old) to early adulthood (23–33 years old). Unfortunately, these studies compared the average search performance and search behavior of groups of participants in broad age ranges, thus losing information regarding individual performance. 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 12 to 19 years, participated in a visual-search task. They 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, half of which 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 (65 female, 75 male) volunteered to participate. Participants were recruited from all six grade levels of a secondary school (Gemeentelijk Gymnasium) in Hilversum, the Netherlands. Admission 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 ($82 \times 82 \times 72$ cm height/width/depth) whose inside was painted black. A chin rest was placed at the front of the booth, and a 17-in. 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 participants 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 1,280 × 1,024 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, Canada) at a frequency of 250 Hz. Search displays were viewed binocularly, but eye movements were recorded from the left eye only and were stored for off-line 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 (1,280 × 1,024 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 six rows of six 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 c/deg (Figure 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.

In 72 of the 144 search displays (*single-frequency displays*), the nontarget 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 1), 18 of the 36 elements had a different orientation from the target as well as a lower spatial frequency (LSF) of 4.82 c/deg. 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 (Hooge & Erkelens, 1999; Wu & Kowler, 2013) and thus provide a peripheral-selection task. The orientation of each of the nontargets in both display types was randomly chosen and varied among ±10°, ±30°, ±50°, ±70°, and ±90° from the vertical. The different orientations were chosen to manipulate the difficulty of the foveal-discrimination task (Wu & Kowler, 2013).

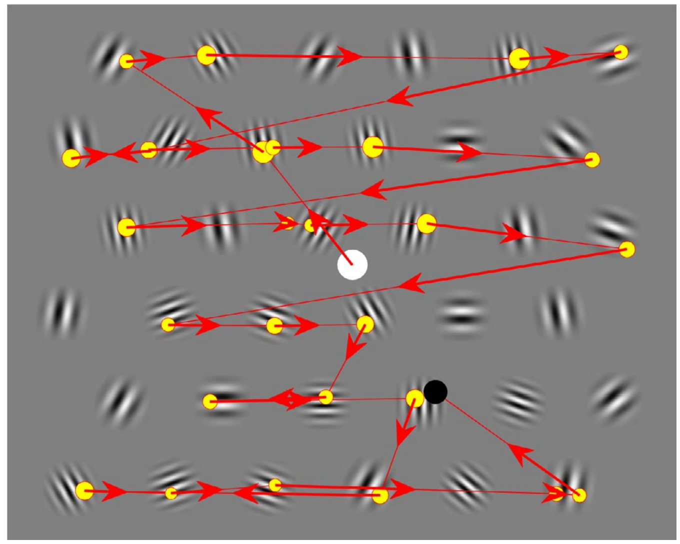

Figure 1. Example of a mixed-frequency display with the target present. In this picture, the stimulus elements have been enlarged for visibility purposes. The target is located in the second row from the bottom, the third element from the right. Drawn on the search display are the fixations (the radius of each dot 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, with the black dot showing 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 low-spatial-frequency elements were skipped and most of the high-spatial-frequency elements fixated upon.

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 heads were placed in a chin rest, and the eye tracker was placed on their heads. The participants performed four practice trials—one of each display type (mixed- or high-frequency) with the target present or absent. The experimenter verified the responses and reminded participants 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 the 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 space bar. Upon a press of the space bar, the screen went blank, and after a random delay of 0.5–2.0 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 min. Eye-movement recordings, display presentations, keyboard handling, and timing were controlled by custom-written scripts in Experiment Builder (v. 1.10.165, SR Research, 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 (one female, two male) 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 19,584 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 was 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 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 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 time stamps and the fixation location were extracted from the calibrated eye-position data. These data were exported and analyzed using 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 deviation of the intersample distances (Holmqvist et al., 2011, p. 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 from those 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. For 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, p. 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, Cohen, West, and Aiken (2013) and implemented by Soper (2017). 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 analysis of variance with two within-subject factors: spatial frequency (two levels: HSF and LSF) and orientation (five 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 analysis of variance with one within-subject factor: orientation (five 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 analysis of variance with two within-subject factors: display type (two levels: mixed and single frequency) and orientation (five 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 earlier.

Statistical analyses were performed using IBM SPSS statistical software (v. 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 $\alpha = 0.05$.

Results

A total of 136 participants completed the task without any problems: 72 male (52.9%, ages: 12.4 to 18.8 years; $M \pm SD$: 15.5 ± 1.92) and 64 female (47.1%, ages: 12.5 to 18.5 years; $M \pm SD$: 15.4 ± 1.96). The individual root-mean-square values of intersample 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 19,584 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 decreased 0.150 s per year, 95% confidence interval (CI) [–0.270, –0.029]. This decrease

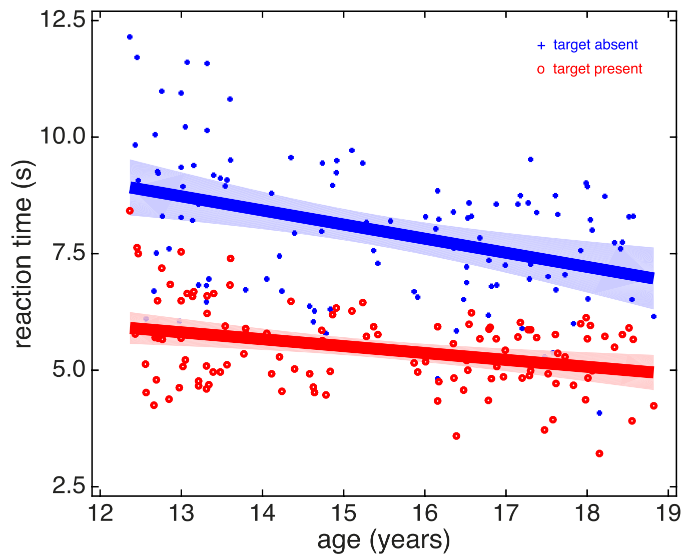

Figure 2. Average reaction time per trial for each participant for correctly answered target-absent and target-present trials. The shaded areas each represent a 95% confidence interval.

was not significantly affected by target presence, $t(268) = 1.316$, $p = 0.189$ (Figure 2).

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

Response accuracy

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, about 45 min, demanded prolonged attentional focus from 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 with and significantly different between the two halves of the task—reaction time: $r = 0.788$, $p < 0.001$; accuracy: $r = 0.451$, $p < 0.001$. During the second half of the task, reaction time was shorter than during the first half (first half: 8.89 ± 2.11 s; second half: 7.71 ± 1.77 s; Cohen's $d = 0.605$), $t(135) = 10.559$, $p < 0.001$, and accuracy was lower (first half: 0.90 ± 0.08; second half: 0.88 ± 0.08; Cohen's $d = 0.250$), $t(135) = 2.428$, $p < 0.001$.

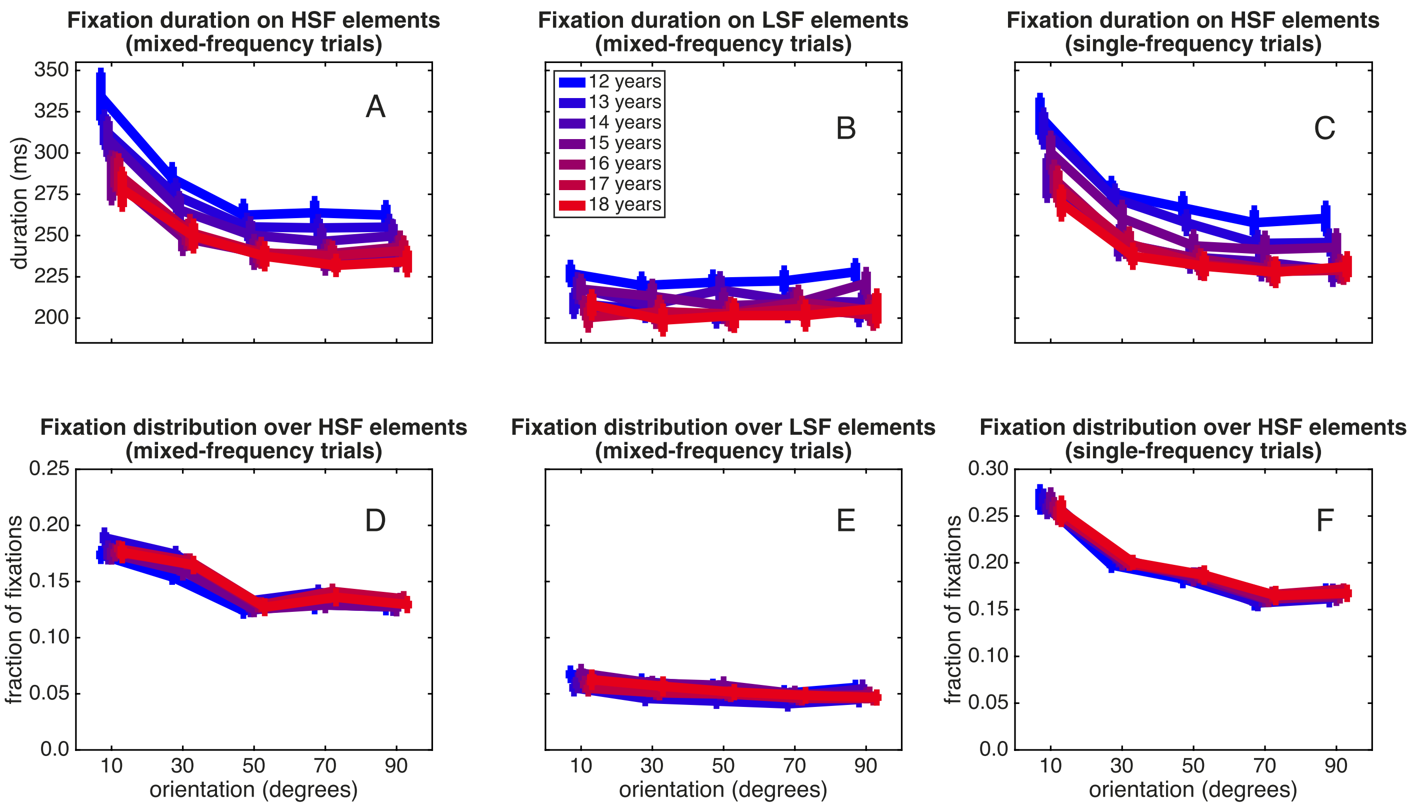

Figure 3. Results concerning the mixed-frequency trials are depicted in fixation duration on (A) high-spatial-frequency (HSF) and (B) low-spatial-frequency (LSF) elements and fixation distribution over (D) HSF and (E) LSF elements. For the single-frequency trials, the fixations durations on HSF elements are depicted in (C) and the fixation distribution over the HSF elements with different orientations in (F). 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.

Fixation duration

The average fixation duration (Figure 3A and 3B) was significantly correlated with age, $r = 0.306$, $p < 0.001$, with a slope of the fixation duration versus age of –4.93 ms/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, 95% CI [–5.153, –0.545]—$t(268) = 1.86$, $p = 0.064$, or orientation; the largest difference in slopes was between HSF –10° (slope = –8.278, 95% CI [–12.555, –4.002]) and HSF –90° (slope = –4.180, 95% CI [–7.031, –1.330]), and was not significant, $t(268) = 1.58$, $p = 0.116$; all other combinations of orientations: $t(268) < 1.429$, $p > 0.154$.

Spatial frequency had a significant effect on 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 for HSF elements but not LSF elements—respectively: $F(4, 132) = 99.4$, $p < 0.001$, $\eta^2 = 0.751$ (Figure 3A); $F(4, 132) = 2.17$, $p = 0.076$, $\eta^2 = 0.062$ (Figure 3B). Fixation duration was strongly and positively correlated with reaction time, $r = 0.517$, $p < 0.001$, but not response accuracy, $r = –0.139$, $p = 0.106$.

Number of fixations

The number of fixations was not significantly correlated with age, $r = –0.037$, $p = 0.667$. It 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, $r = 0.844$, $p < 0.001$, and response accuracy, $r = 0.461$, $p < 0.001$.

Distribution of fixation locations

We found no significant correlation of age with the distribution of fixation locations (Figure 3C and 3D) 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 that were 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 that were most similar to the target. This effect, though, was much stronger for HSF elements than LSF elements—respectively: $F(4) = 567$, $p < 0.001$, $\eta^2 = 0.808$ (Figure 3C); $F(4) = 57.5$, $p < 0.001$, $\eta^2 = 0.299$ (Figure 3D).

Comparison of results between display types

Within the single-frequency trials, we found the same correlations of age and 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 orientation, with the largest difference—found between HSF −10° (slope = −8.985, 95% CI [−12.846, −5.123]) and HSF −70° (slope = −4.751, 95% CI [−7.423, −2.079])—not being significant, $t(268) = 1.784$, $p = 0.076$; all other combinations of orientations of HSF elements: $t(268) < 1.759$, $p > 0.080$. 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 $d = 0.115$, $t(135) = 21.1$, $p < 0.001$. 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.

Reaction time decreased significantly with age (Figure 2). Earlier studies with younger children have also reported a decrease of reaction time with age (Huurneman & Boonstra, 2015; Seassau & Bucci, 2013), and an increase of reaction time with age has been reported 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 3A and 3B). 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 the decrease: approximately 5 ms/year. The detection limit for grating acuity for 10- to 20-year-olds has previously been reported to be in the range of 27–33 c/deg (Skoczenski & Norcia, 2002). The finest grating used in the present study was 8.19 c/deg. However, search times have been shown to increase at factors of up to 5 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 earlier reports of 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 subtask increases until the end of adolescence independent of the difficulty of the task.

Even though the difficulty of 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 fixations over the different elements (Figure 3). Elements more similar to the target were fixated upon more often and for longer. The increase in fixation duration as target similarity increased is consistent with reports from earlier studies

(Hooge & Erkelens, 1996; Vlaskamp & Hooge, 2005). Spatial frequency had the strongest effect on fixation duration. Orientation also affected 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 accuracy threshold to be reached. Several of our results support the hypothesis of flexibility in fixation duration rather than 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 that was 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 adolescents than for younger ones, we found no significant difference in accuracy, at either the trial level (response accuracy) or the fixation level (fraction of saccades made to HSF 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 3 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 subtask is already fully developed at the age of 12.

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 subtask was not influenced by the presence of the peripheral-selection subtask. Independent of age, 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 subtask but also the complexity of the peripheral-selection subtask (selection on orientation only versus selection on orientation and spatial frequency) influences 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—that is, 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 (Hooge & Erkelens, 1999; Wu & Kowler, 2013) were performed with adults, whereas our participants were adolescents. It might be interesting for future research to study whether the effect on fixation durations of the complexity of the peripheral-selection subtask might be different for different age groups.

Correlation of search performance with search behavior showed that reaction time was strongly and positively correlated with fixation duration. Both reaction time and fixation duration decreased with age. Previous research with younger children and adults (Huurneman & Boonstra, 2015; Seassau & Bucci, 2013) has 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 response accuracy nor 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, both number of fixations and response accuracy 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, they lost some interest and motivation. Depending on the aims of future studies, researchers 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 those that 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 of 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 yet have reached a stable threshold during childhood (Skoczenski & Norcia, 2002).

In conclusion, search performance and search behavior change during adolescence. Speed of foveal discrimination increased with age, while efficiency of peripheral selection did not change. 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.

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

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