Target–distractor similarity has a larger impact on visual search in school-age children than spacing

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In typically developing children, crowding decreases with increasing age. The influence of target–distractor similarity with respect to orientation and element spacing on visual search performance was investigated in 29 school-age children with normal vision (4- to 6-year-olds \(N = 16\), 7- to 8-year-olds \(N = 13\)). Children were instructed to search for a target E among distractor Es (feature search: all flanking Es pointing right; conjunction search: flankers in three orientations). Orientation of the target was manipulated in four directions: right (target absent), left (inversed), up, and down (vertical). Spacing was varied in four steps: 0.04\(^{\circ}\), 0.5\(^{\circ}\), 1\(^{\circ}\), and 2\(^{\circ}\). During feature search, high target–distractor similarity had a stronger impact on performance than spacing: Orientation affected accuracy until spacing was 1\(^{\circ}\), and spacing only influenced accuracy for identifying inversed targets. Spatial analyses showed that orientation affected oculomotor strategy: Children made more fixations in the ‘‘inversed’’ target area (4.6) than the vertical target areas (1.8 and 1.9). Furthermore, age groups differed in fixation duration: 4- to 6-year-old children showed longer fixation durations than 7- to 8-year-olds at the two largest element spacings \((p = 0.039\) and \(p = 0.027\)). Conjunction search performance was unaffected by spacing. Four conclusions can be drawn from this study: (a) Target–distractor similarity governs visual search performance in school-age children, (b) children make more fixations in target areas when target–distractor similarity is high, (c) 4- to 6-year-olds show longer fixation durations than 7- to 8-year-olds at 1\(^{\circ}\) and 2\(^{\circ}\) element spacing, and (d) spacing affects feature but not conjunction search—a finding that might indicate top-down control ameliorates crowding in children.

Introduction

Crowding, the inability to identify objects surrounded by clutter, and visual search are said to be intrinsically limited by attention (Carrasco, 2011). Evidence is accumulating that crowding, or critical spacing, can be modulated by attention; e.g., studies in adults show that cueing reduces crowding (Freeman & Pelli, 2007; Strasburger, 2005), and so does pop-out (Kooi, Toet, Tripathy, & Levi, 1994; Scolari, Kohnen, Barton, & Awh, 2007; Whitney & Levi, 2011). Developmental research shows that young children have limited attentional capacity, reflecting the immaturity of underlying neural substrates, for example, unmyelinated axons and developing frontal lobes (Cunningham & McKay, 1994; Posner & Rothbart, 2005). Frontal functions are not fully mature until late adolescence (Kolb et al., 2012). Attention appears to be one of the explanations for stronger central crowding in children than in adults (Atkinson, Anker, Evans, Hall, & Pimm-Smith, 1988; Jeon, Hamid, Maurer, & Lewis, 2010). A recent study showed that infants aged 6–15 months do not yet have the ‘‘fine-grained’’ spotlight of attention that adults possess but

have a more diffuse “lantern,” which limits the resolution with which information is assessed (Farzin, Rivera, & Whitney, 2010). Peripheral crowding effects in children aged 10–17 years adhered to Bouma’s law, which describes that flankers placed at a distance larger than 0.5 × eccentricity do not interfere with target recognition (Tadin, Nyquist, Lusk, Corn, & Lappin, 2012). In sum, both foveal and peripheral crowding are phenomena that are strongly influenced by developmental factors. In this paper, we will investigate how target–distractor similarity and element spacing affect visual search in school-age children with normal visual development.

Several principles apply to (crowded) visual search. The first is that target–distractor similarity influences crowded visual search. Greater similarity makes visual search more difficult (Vlaskamp & Hooge, 2006; Whitney & Levi, 2011). Or, vice versa, deviation from the crowd pops out; it breaks crowding (Cavanagh, 2001). Recent studies demonstrate this principle by showing that the magnitude of both foveal and peripheral crowding depends on whether a target groups or ungroups from the distractors (Manassi, Sayim, & Herzog, 2012, 2013; Sayim, Westheimer, & Herzog, 2011). The second principle is that decreased element spacing can induce stronger crowding, which can be observed by longer search times (Vlaskamp & Hooge, 2006). A decrease in element spacing evokes longer fixation durations in children and adults with normal vision (Huurneman, Cox, Vlaskamp, & Boonstra, 2014; Moffitt, 1980; Vlaskamp & Hooge, 2006; Vlaskamp, Over, & Hooge, 2005). Element spacing influences eye movements, e.g., fixation duration is affected by task difficulty (Moffitt, 1980). The third principle is that crowding, induced by high target–distractor similarity and/or small element spacing, can have a dual role in visual search, depending on spacing regularity. Regularity of element spacing plays an important role: Regular spacing can lead to the perception of a single, coherent, texture-like stimulus, in which case it is more difficult to identify individual elements (Saarala, Westheimer, & Herzog, 2010). With irregular spacing, distractors similar to the target deteriorate the quality of the peripheral signal but can also attract eye movements because more of the target property is present at the location of the distractor (de Vries, Hooge, Wiering, & Verstraten, 2011). This way, stronger lateral masking can lead to shorter search times. However, small spacing can also lead to longer search times and a degradation of saccadic search (Huurneman et al., 2014; Vlaskamp & Hooge, 2006). The differences between the two studies described above may be attributed to spacing regularity. Small spacing thus attracts eye movements when spacing is irregular (de Vries et al., 2011), but in a regularly spaced grid, small spacing increases crowding and degrades search performance (Vlaskamp & Hooge, 2006). The fourth principle is that patterns with discriminable elements and small element spacing can be segregated more easily than patterns in which the same elements are more widely spaced (Nothdurft, 1993; Scolari et al., 2007). At present, it is unclear to what extent these principles are applicable to search in school-age children.

Visual search is easier when the target is defined by one feature, such as color or orientation, than when it is defined by a conjunction of two or more features, such as color and orientation, partly because during conjunction search the target and the distractors tend to be more similar to each other (Treisman & Gelade, 1980). Use of a distinct feature for the target (such as a unique color or orientation) can have a beneficial effect because the feature will “pop out.” This enables attention to be directed to the information at that location. Preschool children essentially show the same feature search performance as adults but have steeper search slopes for conjunction search (Thompson & Massaro, 1989). Weaker conjunction search performance compared to feature search performance in children has been reported earlier (Hommel, Li, & Li, 2004; Lobaugh, Cole, & Rovet, 1998). In a recent study, we observed that crowding ratios, which can be calculated by dividing single with linear visual acuity and can be seen as an index for the strength of crowding, were not correlated to feature search performance but were related to conjunction search with small spacing and heterogeneous distractors (Huurneman et al., 2014). This might be explained by a reduction of crowding by grouping of the distractors separately from the target during feature search (Whitney & Levi, 2011).

Part of this data set was published recently in a paper in which differences with regards to feature search performance between children with normal vision and children with nystagmus are reported (Huurneman & Boonstra, 2014). In the former paper, only the effect of spacing was investigated. In the present paper, the influence of target–distractor similarity with respect to orientation and age category are investigated, and a spatial analysis is provided. The conjunction search data have not been published before.

The present study will evaluate the different effects that orientation and element spacing can have on visual search performance in school-age children. Three hypotheses are evaluated: (a) 4- to 6-year-old children show lower accuracies than 7- to 8-year-old children at smaller spacings, (b) children show longer search times at smaller spacings during conjunction search, and (c) oculomotor measures differ between the two age groups.
Methods

Participants

Twenty-nine children with normal vision participated. Inclusion criteria were age 4–8 years, normal developmental level, normal birth weight (at least 3000 g), birth at term (at least 36 weeks), no perinatal complications, and no motor or intellectual impairments. Children were recruited from regular Dutch primary schools. Table 1 presents the average age and distance visual acuities of the children. Informed consent was obtained from the parents of all participants. A local ethics committee approved the study before the assessments were conducted (CMO Arnhem-Nijmegen). The study was conducted in accordance with the Declaration of Helsinki (1969).

Ophthalmological examination

Visual acuity was assessed before the experiment started and was measured mono- and binocularly at 5 m with the C-test (Haase & Hohmann, 1982) and at 6 m binocularly with the tumbling E-chart (Taylor, 1978) under controlled lighting conditions. Near visual acuity was determined binocularly with the LEA-version of the C-test at 40 cm (Huurneman, Boonstra, Cillessen, van Rens, & Cox, 2012).

Procedure

Children sat at a distance of 60 cm. Viewing was binocular. All children performed the feature search task, which consisted of a total of 16 trials, i.e., 4 (orientation) × 4 (spacing). Before the experiment started, each child performed four exercise trials in order to make sure the child understood the experimental procedure.

All participants conducted a feature search task. During this search task, children were instructed to identify the unique E or, in case there was no unique E, confirm that the target was absent (four options: right [absent], left [inversed], up, and down). Stimuli were presented in a randomized order to avoid measuring influences of learning and exhaustion. The target subtended 2° × 2°, and the stimulus was screen-wide (29° × 25°, see Figure 1). The location of the tumbling E was randomly varied in each quadrant of the screen to make sure the child actively searched for the target. In addition to the feature search task, the 7- to 8-year-olds also conducted a conjunction search task, which also consisted of a total of 16 trials (4 [orientation] × 4 [spacing] levels). The conjunction search task consisted of a display filled with Es of all orientations. In every trial, there was one E that occurred only once in the display. The instruction for the children in the conjunction search task thus was to identify the unique E.

Before the trial started, a fixation cross subtending 2° × 2° was presented for 500 ms, after which an interstimulus interval of 1000 ms followed. The influence of crowding was measured by manipulating spacing with edge-to-edge element spacing of 2.6 min of arc (equal to 0.04°), 0.5°, 1°, and 2°. A new trial was presented after the child pressed the response button matching the target (see Figure 1). There was no time limit for the child’s response.

Apparatus

Stimuli were generated by a Windows XP computer and presented on a 17-in. monitor with integrated eye trackers (Tobii T120, Tobii Corporation, Danderyd, Sweden). Screen resolution was set at 1280 × 1024 pixels, pixel size 0.27 mm × 0.27 mm². Stimulus presentation was driven by Delphi software. Head positions of the children were not fixed. A rule was incorporated into the stimulus-presentation software in order to assure that the children were seated at a proper viewing distance.

When children came closer to the monitor than 60 cm, the stimulus disappeared from the screen. Eye movements were registered at a temporal sampling rate of 60 Hz. Before recording the eye movements, a five-point calibration procedure was performed for both eyes. Fixations were detected offline and were identified with the 1-DT dispersion-based algorithm (Salvucci & Goldberg, 2000). Fixations were detected when the eyes remained within an area of 50 pixels with a minimum duration threshold of 50 ms.

Statistical analysis

Accuracy measures were not normally distributed. Nonparametric tests were used to analyze effects of spacing, orientation, and age category on accuracy. The first step was to compare accuracies between age categories with the Mann-Whitney U test (two levels:
4–6 years vs. 7–8 years). The second step was to conduct a Friedman test to investigate within-subjects effects of orientation (four levels: right [absent], left [inversed], up, and down [vertical targets]) and spacing (four levels: 0.04°, 0.5°, 1°, and 2°).

Mean search times and eye-movement measures for correct trials were compared with a repeated-measures ANOVA. Age category was entered as a between-subjects variable. In the first repeated-measures ANOVA, orientation was entered as the within-subjects variable. In the second repeated-measures ANOVA, spacing was entered as a within-subjects variable. All analyses were run with the alpha set on 0.05 while using Bonferroni corrections for multiple comparisons. We analyzed the effect of target orientation and element spacing on three oculomotor measures:

1. Number of fixations (mean)
2. Fixation duration (mean)
3. Run count (RC) = number of fixations in the target area

Target areas were defined as the area subtending the target and 1° above, below, and at both sides of the target. High RCs indicate frequent rechecking (Archibald, Hutton, Clarke, Mosimann, & Burn, 2013).

**Results**

**Feature search: Performance measures**

**Accuracy**

No differences in accuracy were found between age categories (at 0.04°: $U = 145.00$, $z = 2.09$, $p = 0.075$; other $ps > 0.2$). Median accuracies for all trials are presented in Figure 2. Target orientation affected accuracy from 0.04° until 1° spacing: Children were less accurate for identifying inversed than absent and vertical targets (see Tables 2 and 3). Spacing only influenced inversed target identification: Accuracies were lower at 0.5° than at 2° (medians resp. 0% and 100%, $p = 0.007$). Other post hoc effects were not significant ($ps > 0.1$). Target orientation thus had a stronger impact on accuracy than spacing.

**Search time**

**Effect orientation:** Search times were affected by target orientation at 0.04°, 1°, and 2°: 0.04°, $F(3, 42) = 8.48$, $p = 0.004$, partial $\eta^2 = 0.38$; 1°, $F(3, 36) = 8.86$, $p < 0.001$, partial $\eta^2 = 0.43$; 2°, age $\times$ orientation interaction, $F(3, 63) = 3.58$, $p = 0.019$, partial $\eta^2 = 0.15$. At 0.04°, children were slower for inversed (5.8 s) than vertical targets (2.5 and 2.9 s), $ps = 0.011$ and 0.012 (see Figure 1. The experimental procedure.
3). At 1°, search times were longer for absent than vertical targets, $p = 0.003$ and 0.020. At 0.04° and 1°, no main effect of age or interactions were found, $p > 0.05$. At 2°, only 7- to 9-year-olds’ search times were affected by orientation, $F(3, 27) = 5.14$, $p = 0.006$, partial $\eta^2 = 0.36$. Children were slower for inversed (3.7 s) and downward-pointing target (2.4 s) than upward-pointing target (1.7 s) trials, resp. $p = 0.050$ and $p = 0.007$. In addition, 7- to 9-year-olds (1.7 s) showed shorter search times than 4- to 6-year-olds (2.5 s) for upward-pointing targets at 2°, $F(1, 21) = 13.35$, $p = 0.001$, partial $\eta^2 = 0.39$. At 0.5°, no main or interaction effects were found.

**Effect spacing**: Spacing did not affect search times for any of the targets (all $p > 0.05$). Search times for upward pointing targets differed between age categories, $F(1, 23) = 9.23$, $p = 0.006$, partial $\eta^2 = 0.29$: 4- to 6-year-olds (2.9 s) were slower than 7- to 8-year-olds (1.8 s).

**Oculomotor measures**

**Number of fixations**

**Effect orientation**: Orientation affected the number of fixations made at 0.04°, 1°, and 2° spacing: 0.04°, $F(3, 42) = 6.14$, $p = 0.001$, partial $\eta^2 = 0.31$; 1°, $F(3, 33) = 12.12$, $p < 0.001$, partial $\eta^2 = 0.52$; 2°, $F(3, 54) = 6.81$, $p = 0.001$, partial $\eta^2 = 0.28$. At 0.04°, more fixations were made for inversed (18.2) and upward-pointing targets (12.2) than downward-pointing targets (6.9), $p = 0.012$ and $p = 0.022$ (see Figure 4). At 1° and 2°, children...
made two to three times more fixations during horizontal target trials than vertical target trials ($p < 0.05$). At $0.5^\circ$, no main or interaction effects were found.

**Effect spacing:** A main effect of spacing was found for absent and upward-pointing targets: absent, $F(3, 66) = 2.79, p = 0.047$, partial $\eta^2 = 0.11$; up, $F(3, 54) = 4.92, p = 0.004$, partial $\eta^2 = 0.22$, but post hoc tests were not significant in both cases. No age or interaction effects were found. For inversed and downward-pointing targets, no main or interaction effects were found.

**Fixation duration**

**Effect orientation:** At $0.5^\circ$ and $2^\circ$, orientation influenced fixation duration: ($0.5^\circ$, $F(3, 18) = 3.33, p = 0.043$, partial $\eta^2 = 0.36$; $2^\circ$, orientation × age category interaction, $F(3, 54) = 6.48, p = 0.001$, partial $\eta^2 = 0.27$). At $0.5^\circ$, fixation duration was longer for absent (244 ms) than upward-pointing targets (181 ms), $p = 0.050$. At $2^\circ$, orientation affected 4- to 6-year-olds’ fixation duration, $F(3, 30) = 4.83, p = 0.007$, partial $\eta^2$: fixation durations were longer for inversed (269 ms) than absent target trials (199 ms), $p = 0.020$. Fixation duration in 7- to 8-year-olds was also affected by orientation, $F(3, 24) = 6.52, p = 0.002$, partial $\eta^2 = 0.45$: fixation duration was longer for upward-pointing targets (252 ms) than absent and inversed targets (187 and 183 ms), $p = 0.035$ and 0.002. At $1^\circ$, age category influenced fixation duration, $F(1, 11) = 5.48, p = 0.039$, partial $\eta^2 = 0.33$: 4- to 6-year-olds fixated longer (256 ms) than 7- to 8-year-olds (206 ms). At $2^\circ$, age groups differed in fixation duration for inversed targets, $F(1, 20) = 5.71, p = 0.027$, partial $\eta^2 = 0.22$: 4- to 6-year-olds fixated longer (259 ms) than 7- to 8-year-olds (196 ms). At the smallest spacing ($0.04^\circ$), no main effects or interactions were found (see Figure 5).

**Effect spacing:** Spacing affected fixation durations for all target orientations: absent, $F(3, 66) = 6.18, p = 0.001$, partial $\eta^2 = 0.22$; inversed, $F(3, 18) = 3.72, p = 0.031$, partial $\eta^2 = 0.38$; upward, $F(3, 54) = 5.31, p = 0.003$, partial $\eta^2 = 0.23$; downward, $F(3, 51) = 2.78$.

Table 3. Confusion matrix for feature search showing how often Es were reported as absent/rightward (A), inversed (I), upward (U), or downward (D).

<table>
<thead>
<tr>
<th>Spacing</th>
<th>Absent</th>
<th>Inversed</th>
<th>Up</th>
<th>Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.04^\circ$</td>
<td>A:28</td>
<td>A:12</td>
<td>A:2</td>
<td>A:1</td>
</tr>
<tr>
<td></td>
<td>I:1</td>
<td>I:16</td>
<td>I:0</td>
<td>I:0</td>
</tr>
<tr>
<td></td>
<td>U:0</td>
<td>U:1</td>
<td>U:25</td>
<td>U:6</td>
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<td></td>
<td>D:0</td>
<td>D:0</td>
<td>D:2</td>
<td>D:22</td>
</tr>
<tr>
<td>$0.5^\circ$</td>
<td>A:28</td>
<td>A:21</td>
<td>A:1</td>
<td>A:1</td>
</tr>
<tr>
<td></td>
<td>I:1</td>
<td>I:7</td>
<td>I:0</td>
<td>I:0</td>
</tr>
<tr>
<td></td>
<td>U:0</td>
<td>U:0</td>
<td>U:27</td>
<td>U:0</td>
</tr>
<tr>
<td></td>
<td>D:0</td>
<td>D:1</td>
<td>D:1</td>
<td>D:28</td>
</tr>
<tr>
<td>$1^\circ$</td>
<td>A:28</td>
<td>A:15</td>
<td>A:0</td>
<td>A:0</td>
</tr>
<tr>
<td></td>
<td>I:1</td>
<td>I:14</td>
<td>I:0</td>
<td>I:0</td>
</tr>
<tr>
<td></td>
<td>U:0</td>
<td>U:0</td>
<td>U:29</td>
<td>U:1</td>
</tr>
<tr>
<td></td>
<td>D:0</td>
<td>D:0</td>
<td>D:0</td>
<td>D:28</td>
</tr>
<tr>
<td>$2^\circ$</td>
<td>A:29</td>
<td>A:6</td>
<td>A:0</td>
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<td></td>
<td>I:0</td>
<td>I:23</td>
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<td>U:0</td>
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<td></td>
<td>D:0</td>
<td>D:0</td>
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</tbody>
</table>

Figure 4. Number of fixations for different element spacings. At $0.5^\circ$ element spacing, the two age groups were combined because sample sizes of separate age groups were too small to analyze separately. Error bars represent standard error of the mean.

Figure 3. Search times for different element spacings. The 4- to 6-year-olds showed longer search times than the 7- to 8-year-olds at $0.04^\circ$ and $2^\circ$ element spacing. Error bars indicate standard error of the mean.
$p = 0.050$, partial $\eta^2 = 0.14$. For inversed targets, fixation durations were longer at $0.04^\circ (237 \text{ ms})$ and $0.5^\circ (243 \text{ ms})$ than at $2^\circ$ spacing (190 ms), respectively $p = 0.029$ and $p < 0.001$. For upward-oriented targets, children fixated longer at $0.04^\circ (309 \text{ ms})$ than $1^\circ (224 \text{ ms})$, $p = 0.047$. For inversed and upward-pointing targets, post hoc tests showed no significant differences ($p > 0.2$). No other main or interaction effects were found.

RC: Number of fixations in target area

**Effect orientation:** At $0.04^\circ$, $1^\circ$, and $2^\circ$, orientation affected RC: ($0.04^\circ$, $F(2, 28) = 15.00$, $p < 0.001$, partial $\eta^2 = 0.52$; $1^\circ$, $F(2, 22) = 5.51$, $p = 0.011$, partial $\eta^2 = 0.33$; $2^\circ$, $F(2, 36) = 4.05$, $p = 0.026$, partial $\eta^2 = 0.18$). At $0.04^\circ$, RCs were higher for inversed (4.6) than vertical targets ($1.9$ and $1.8$), $p < 0.001$ and $p = 0.007$ (see Figures 6 and 7). At $1^\circ$, RC was lower for up ($0.8$) than down targets ($2.1$), $p = 0.010$. No main or interaction effects were found. At $2^\circ$, RCs were higher for up ($1.7$) than down targets ($0.5$), $p = 0.029$. At $0.5^\circ$, no main or interaction effects were found.

**Effect spacing:** Spacing only affected RCs for downward-pointing targets, $F(3, 51) = 19.39$, $p < 0.001$, partial $\eta^2 = 0.53$. RCs were higher at $0.5^\circ (2.6)$ than at $0.04^\circ (1.7)$, $p = 0.040$. In addition, the number of RCs for downward-pointing targets at $2^\circ$ was lower than RCs at all other spacings, $ps < 0.001$ (see Figure 6). Spacing did not affect RCs for inversed and upward-pointing targets ($p > 0.05$). No age or interaction effects were found.

**Conjunction search: Performance and oculomotor measures**

Performance measures were unaffected by spacing during conjunction search ($ps > 0.5$). Mean accuracy was $83.7\%$ and mean search time $10.5$ s. In terms of eye movements, only fixation duration was affected by spacing: children fixated $266$ ms at $0.04^\circ$ and $214$ ms at $2^\circ$, $F(3, 36) = 8.39$, $p < 0.001$, partial $\eta^2 = 0.41$. Number of fixations and RCs were unaffected by spacing ($p > 0.4$). Mean number of fixations was $26.4$, and mean RC was $2.3$.

**Discussion**

The goal of this study was to investigate the influence of target orientation and element spacing on visual search performance in 4- to 8-year-old typically developing children. Three hypotheses were evaluated: (a) 4- to 6-year-old children show lower accuracies than 7- to 8-year-old children at smaller spacings, (b) children show longer search times at smaller spacings during conjunction search, and (c) oculomotor measures differ between the two age groups. In general, our results advocate that target–distractor similarity (orientation) exerts a stronger influence on visual search performance and oculomotor measures than spacing.

Figure 5. Fixation duration for different element spacings. At $0.5^\circ$ element spacing, age groups were combined because sample sizes of separate age groups were too small. Error bars represent standard error of the mean.

Figure 6. RCs (number of fixations in target area) for different element spacings. At $0.5^\circ$ element spacing, age groups were combined because sample sizes of separate age groups were too small. Error bars indicate standard error of the mean.

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Differences in accuracy between age categories

No empirical support was found for the first hypothesis; there were no differences in accuracy between 4- to 6-year-old and 7- to 8-year-old children. Although no differences in accuracy between age groups were found, accuracy for identifying an inversed target was severely affected by spacing. Children showed a median accuracy of 0% for identifying inversed targets at 0.5°, a significantly poorer performance than inversed target recognition at 2° (median accuracy 100%, $p = 0.007$). At the largest spacing, target orientation no longer had an impact on accuracy.

A first explanation for these low accuracies for inversed target recognition could be left–right confusion. Before children learn how to read, they often make errors such as mirror-writing of letters or entire words, which indicates orientation confusion. Ample literature indicates that a left–right confusion is observable in young children between the ages of 5 to 10 years; children of this age are susceptible to make reversal errors, such as “b, d” (Boone & Prescott, 1968; Cairns & Steward, 1970; Kaufman, 1980; Rigal, 1994; Rudel & Teuber, 1963; Simons, 1983). However, this explanation does not cover the results because one would also expect low accuracies for the report of target-absent trials (which did not occur). Therefore, visibility factors must play a larger role than left–right confusion.

A more plausible explanation that takes poorer visibility into account and might explain results better is peripheral crowding. Although not much is known about peripheral crowding effects in school-age children, studies investigating foveal crowding in children with normal vision have been conducted since the early 1980s (Atkinson et al., 1988; Huurneman, Boonstra, Cillessen, et al., 2012; Norgett & Siderov, 2011; Semenov, Chernova, & Bondarko, 2000). It is a much replicated finding that children experience stronger foveal crowding than adults (Huurneman, Boonstra, Cillessen, et al., 2012; Norgett & Siderov, 2011). A low target signal might explain the poor search performance of children when identifying an inversed target. Children who did show correct answers for inversed target recognition made more fixations in the target area during an inversed target trial than during trials with vertical targets. It is unlikely that the lower accuracies for inversed target identification can be solely explained by left–right confusion because there was also a difference in eye
movement behavior between inversed target trials and trials with vertical targets. The number of times the children moved their eyes into the inversed target area was significantly higher than the number of times children entered vertical target areas, which can be considered to be evidence for a decreased target signal due to greater target–distractor similarity (Pelli, Palomares, & Majaj, 2004).

An additional explanation for the low accuracy for inversed targets might be that children used a truncated search strategy during feature search. This explanation complements the former explanation because orientation affected accuracy until spacing was sufficiently large (i.e., 2°). Children did not look at all items during feature search and showed average search times of about 1.5–2.5 s for vertical targets (these targets popped out, and during these searches, spacing did not affect accuracy or search time). Search times were about two times longer for target-absent and inversed-target trials than for vertical targets. Children might have used the following strategy: Check if the target pops out during the first second or two (report if it does); if not, look for the inverted or absent target for another second or two (report target if it is found); if not, report absent.

Recent studies link foveal and peripheral crowding effects: There may be overlapping principles of grouping, which, in some situations, can explain both peripheral and central crowding effects (Manassi et al., 2012). The longer search times and lower accuracies are unlikely to be explained by central crowding because targets were large enough for all children to see. Therefore, a more valid explanation might be that peripheral crowding restricted children in their ability to perceive the target. Evidence for this explanation can be found in our eye-movement recordings. For example, RCs, i.e., the number of times the child entered the target area during a trial (Archibald et al., 2013), were considerably higher for inversed than vertical targets, suggesting that children had to foveate the inversed target to give a correct answer.

Performance measures, number of fixations, and RCs were unaffected by spacing during conjunction search. This finding that spacing did not affect the accuracy or search times during conjunction search in children with normal vision is in line with an earlier study in which small elements (0.67°) were presented in a 4 × 4 grid (Huurneman et al., 2014). The instruction for the conjunction search task was to identify the unique E that appeared once in the display. The majority of children adopted a strategy that they described as “I am going to look for the unique E by checking which Es are present more than once. Then the answer will be the E that I have not seen twice and appears to be the least frequent.” Some children checked all the elements standing in the first row of the stimulus and then concluded that they found the target because they saw which Es were present more than once. In other words, the answer was reached by a process of elimination and had a demand on working memory. Pilots with 6-year-olds showed that these children did not yet adopt this strategy.

The size of the elements (2° × 2°) and the absence of grouping cues in the conjunction search task might explain the lack of spacing effects. Children had to segregate individual elements that could not be grouped together. The segregation of elements thus seemed to be easier for the 7- to 8-year-olds for a conjunction search task than for a feature search task in which distractors could be grouped. Accuracies of the 7- to 8-year-olds were lower for feature search with inversed targets (median 0% at 0.5°) than for conjunction search (mean accuracy 83.7%). This finding illustrates the strong adverse influence of target–distractor grouping on search performance and the ameliorating effect of a task-induced cognitive top-down strategy, which seems to relieve crowding.

Differences in oculomotor measures between age groups

Our third hypothesis was confirmed: There were difference in eye movements between 4- to 6-year-olds and 7- to 8-year-olds. The 4- to 6-year-olds showed longer fixation durations than 7- to 8-year-olds at 1° and 2° element spacing. No other differences in oculomotor measures were found between the two age groups.

An explanation for the longer fixation durations in younger children can be that children found the task harder as task difficulty has been presented as a reason for longer fixations (Moffitt, 1980). However, longer fixation durations for children than adults during word reading have been described earlier, and with regards to reading, fixation duration decreases with age (Seassau & Bucci, 2013). Longer fixation durations in younger children were also apparent during visual search and...
were suspected to be a sign of immature oculomotor mechanisms (Bucci, Nassibi, Gerard, Bui-Quoc, & Seassau, 2012). The ability to maintain steady fixation on a target increases with age (Aring, Gronlund, Hellstrom, & Ygge, 2007; Ygge, Aring, Han, Bolzani, & Hellstrom, 2005). Young children show more intrusive saccades during steady fixation on a target than older children (Kowler & Martins, 1982). Although this ability to fixate steadily on a target improves with age, and uninterrupted periods of fixation were observed in the abovementioned studies, we observed that 7- to 8-year-old children actually fixated shorter than the 4- to 6-year-olds during feature search.

In the light of the abovementioned studies, an explanation for the shorter fixations might be that older children show better oculomotor skills, more stable fixations, and therefore suffice with shorter fixation durations than younger children. Fixation stability increases with age (Aring et al., 2007; Kowler & Martins, 1982), and more stable fixations may allow shorter target inspections during an easy search task or an automated task such as reading. There may exist a U-curve for fixation duration in development in which saccadic latency is correlated with executive functions (Perneczky et al., 2011), which in this task might translate itself in the 7- to 8-year-olds showing shorter saccadic latencies than the 4- to 6-year-olds. Weaker executive functioning leads to longer saccadic latencies and thus longer fixation duration: This has been observed in adults with Parkinson’s disease who show longer fixation duration than age-matched adults (Archibald et al., 2013; Perneczky et al., 2011).

The extent to which our results can be generalized is limited because we only measured the effect of target orientation on search performance with tumbling Es. Our results would be more solid if we also had used different distractor orientations, letters, contrasts, and/or colors. Future studies should present children with different conditions so that more generalized conclusions can be drawn with respect to the influence of target–distractor similarity on search performance.

A methodological limitation of the present study is the small number of trials that were used. Although more work is needed to further investigate the role of masking in search, we did succeed in uncovering some principles of crowded search in children with normal visual development and came across some unexpected findings.

Conclusions

The first, and most important, finding is that target–distractor similarity was the principle that governed the visual search performance in school-age children. Performance was mainly affected by target–distractor similarity: Higher target–distractor similarity influenced accuracy of visual search from 0.04° until at least 1° element spacing. The second finding is that search performance was weakest for the identification of the inversed target at 0.5° element spacing. Eye-movement measures showed that children who provided correct answers entered the target area more frequently if the target was inversed compared to when the target was vertical and stood out from the crowd. Children with incorrect answers generally did not enter the target area. We therefore conclude that the most likely mechanism underlying weaker search performance for inversed target recognition is masking.

Keywords: children, visual search, eye movements, crowding, masking
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