Eye Movements, Strabismus, Amblyopia and Neuro-Ophthalmology

# Impact of Amblyopia on Visual Attention and Visual Search in Children

Alex A. Black, Joanne M. Wood, Silvie Hoang, Eloise Thomas, and Ann L. Webber

Centre for Vision and Eye Research, School of Optometry and Vision Science, Queensland University of Technology, Kelvin Grove, Brisbane, Australia

Correspondence: Alex A. Black, Centre for Vision and Eye Research, School of Optometry and Vision Science, Queensland University of Technology, Kelvin Grove, Brisbane, QLD 4059, Australia; aa.black@qut.edu.au.

**Received:** November 16, 2020
**Accepted:** March 19, 2021
**Published:** April 13, 2021

Citation: Black AA, Wood JM, Hoang S, Thomas E, Webber AL. Impact of amblyopia on visual attention and visual search in children. *Invest Ophthalmol Vis Sci.* 2021;62(4):15. https://doi.org/10.1167/iovs.62.4.15

**Purpose.** The purpose of this study was to compare binocular visual attention, visual processing speeds, and visuo-cognitive search ability in children with and without amblyopia and investigate the association of visual acuity and binocular function with these measures.

**Methods.** Participants included 20 children with amblyopia (mean age = 9.0 ± 1.2 years; 15 anisometropic and 5 strabismic) and 20 children with normal vision development (9.5 ± 1.7 years). Vision assessment included visual acuity (monocular and binocular) and binocular function (Worth 4 Dot and Randot Preschool Stereotest). Visual attention and processing speeds were assessed using the three subtests of the Useful Field of View (UFOV; central processing, divided attention, and selective attention). Visuo-cognitive search was measured using static and dynamic presentations of the Trail Making Tests (TMTs), parts A and B, with increasing levels of executive function demand. All children performed these tasks binocularly.

**Results.** Children with amblyopia demonstrated slower visual processing times on the UFOV ($P = 0.04$), and slower completion times on the TMT search tests ($P = 0.014$), compared to controls. TMT performance for children with amblyopia was also more negatively impacted with increasing executive function demands on the TMT part B, compared to controls ($P = 0.005$). Binocular visual acuity was associated with TMT ($P = 0.006$) and UFOV ($P = 0.07$) performance, but none of the other visual function measures were related to performance on these tasks.

**Conclusions.** Children with amblyopia exhibit deficits in higher-order visual processing skills, including visual attention and visual search, particularly with increasing executive function demands. These findings have implications for understanding the impact of amblyopia on everyday function in children.

Keywords: amblyopia, spatial attention, visual search, children

Amblyopia is a neurodevelopmental disorder, affecting three to five percent of the population, that limits visual acuity and impairs binocular sensory perception.[1] Optimal binocular vision development requires sensory fusion of concordant retinal images during the formative postnatal critical period that can extend up to 8 years of age.[2] Frequent ocular misalignment (strabismus), unequal retinal images from uncorrected refractive error (anisometropia), or stimulus deprivation (e.g. from cataract) early in life can alter visual neurodevelopment and cause amblyopia. Reductions in visual acuity, stereoacuity, vernier acuity, and contrast sensitivity have been widely recognized as consequences of amblyopia.[1,3] Although ocular structures appear normal on clinical examination, visual pathway structures are altered, with changes measurable at the lateral geniculate nucleus and visual cortex, primarily V1, and further to the extrastriate cortex.[4,5]

In addition to the functional vision loss associated with amblyopia, there is a growing body of literature that reports the detrimental impact of amblyopia on performance of everyday activities.[6] In particular, reduced proficiency has been reported on visually guided tasks, including reading[7,8] and visuomotor skills, such as reaching and grasping, drawing, writing, and timed manual dexterity tasks.[9–11] Visually guided saccadic eye movements, reach to touch, and reaching and grasping are all poorer in patients with amblyopia than in controls.[12–17] These functional performance tasks require visual input, yet traditional clinical measures of vision, such as visual acuity and stereoacuity, do not fully explain the everyday performance impairments reported in children with amblyopia. Indeed, whereas some of the variance in performance of individuals with amblyopia can be attributed to the visual losses that can be measured clinically, such as acuity loss or deficits in depth perception, less than 50% of variance is explained by these clinical measures.[10] In addition to visual resolution and depth perception, skilled performance on visually directed functional tasks involves visual attention, as well as higher-order visual processes.

Visual attention is an important visual perceptual process linked to many activities of daily living. It is a multifaceted cognitive process that allows an individual to selectively process visual information and prioritize task-relevant information.[18] It is influenced by top-down (goal-oriented) and bottom-up (salient features) control processes,[19] and operates using both overt (fixating directly toward an area of interest) and covert (directing attention to an area using peripheral vision) attention. Visual search is reliant on visual attention, typically involving active scanning of the visual environment for a specific target among other distractor targets. Executive function plays an important role in aspects of visual search, particularly in planning and performing actions relevant to the task, while ignoring irrelevant information and exhibiting inhibitory control.[20]

Visual search deficits have been reported in adults with amblyopia.[21–24] Deficits in response time for complex visual decisions, suggesting impaired higher-order perceptual performance, have been reported in adults with amblyopia.[25] Deficits in attentive tracking of single and multiple objects in both the amblyopic and fellow eye have also been reported in children with both strabismic and anisometropic amblyopia, suggesting impaired functioning of the parietal cortex.[21] However, although these previous studies have tested higher order processes during monocular viewing with the amblyopic versus non-amblyopic eye, none have examined attentional performance under habitual binocular viewing conditions, which would inform understanding of the broader functional consequence of amblyopia. Although visual attention deficits have been reported in children with hyperopic refractive errors,[26] no studies have assessed the impact of amblyopia on divided and selective visual attention, or on tests of visual search and scanning under binocular viewing test conditions. This gap in the literature is particularly relevant, given novel and emerging treatments for amblyopia, such as dichoptic training, perceptual learning, and video gaming. For example, short 2-week duration binocular video or game-based treatments for childhood amblyopia have been shown to improve binocular visual outcomes,[27] and improve fine motor skills performance.[28] A meta-analysis of the outcomes from these emerging behavioral treatments suggests that improved visual attention resulting from these treatments may help facilitate amblyopia recovery.[29]

A number of tests have been developed to assess these higher-order functional skills, some of which include executive function, and are associated with performance of everyday tasks. Although many of these tests were designed primarily for use with older adults to explore their difficulties with a range of everyday tasks, some also have the potential to be used in younger populations, such as the Useful Field of View (UFOV) and Trail Making Tests (TMTs).

The UFOV is a computer-based assessment of visual attention and speed of visual processing, that includes increasingly complex tasks, requiring detection, identification, and localization of briefly presented central and peripheral targets.[30] The UFOV has been used extensively in older adults, where deficits in UFOV performance have been associated with functional impairments in everyday activities, including motor vehicle crash risk and increased risk of falling.[31] However, this test has also been demonstrated to be a suitable tool for assessing visual perception in children with early brain dysfunction or visual deficits, with normative data being reported for children aged 5 to 15 years.[30]

The TMT is an established neuropsychological instrument that assesses visual search and scanning, psychomotor speed, and executive function, with age and education level normative data available.[32] TMT-A outcomes relate to measures of visual scanning, handwriting speed, and visuomotor processing speed, whereas TMT-B outcomes relate to executive function control, such as working memory, inhibition, and task-switching.[33] Large-scale brain networks including prefrontal and parietal structures are purported to mediate TMT performance.[34] Tablet or computer TMT versions have been recommended to limit the motor component that is required to complete the highly coordinated and goal-directed drawing movements involved in this task.[34]

The purpose of the current study was to examine the impact of amblyopia in children on tests of higher order visual processing with varying levels of executive function demands, including visual attention, visual processing speeds, and visual search under habitual binocular viewing conditions, using UFOV and TMT tasks. A secondary aim was to explore whether clinical visual function measures are associated with these visual performance outcomes. The findings of this study are important to better understand the visual pathway deficits that underly the documented functional consequences of amblyopia on everyday function in children.

## Methods

### Participants

The study included children with anisometropic or strabismic amblyopia, aged between 7 and 13 years, and a comparison group of children with normal vision, recruited from the optometry practice of one of the authors (A.W.) or referred from pediatric ophthalmologists. Amblyopia was defined as visual acuity (VA) in the amblyopic eye from 6/9 to 6/48 (0.2 to 0.9 logMAR), VA in the non-amblyopic eye of 6/7.5 (0.1 logMAR) or better, an inter-eye acuity difference of 2 or more lines (0.2 logMAR) and the presence or history of amblyogenic strabismus and/or anisometropia ($\geq$1.00 D difference in refractive error between eyes). Baseline measures were made following at least 16 weeks of optical treatment (correction of refractive error) if required. Thirteen of the children with amblyopia (65%) had undergone patching or atropine treatment in addition to any required optical treatment prior to entering the study, however, they had persistent but stable VA deficits despite previous amblyopia penalization treatment (see Supplementary Table). The comparison group of visually normal children had VA of 6/7.5 (0.1 logMAR) or better in each eye, an inter-eye acuity difference of 1 line or less (0.1 logMAR), normal stereopsis (40 secs of arc with the Randot Preschool Stereoacuity Test) and no history of treatment for amblyopia or the presence of any amblyogenic condition.

The study was conducted in accordance with the requirements of the Queensland University of Technology Human Research Ethics Committee. All participants were given a full explanation of the experimental procedures and written informed consent was obtained from both parent and child. The option to withdraw from the study at any time was explained to both parents and children. All protocols were in accord with the guidelines of the Declaration of Helsinki.

### Visual Function Assessment

Threshold monocular and binocular VA with optimal refractive correction were measured using a computerized Early Treatment Diabetic Retinopathy Study (ETDRS) chart, as per the Amblyopia Treatment Study VA protocol.[35] Threshold VA (in logMAR units) was scored on a letter-by-letter basis.


**Figure 1.** Schematic of the Useful Field of View (UFOV) assessing central processing (subtest 1), divided attention (subtest 2) and selective attention (subtest 3).

The level of binocular function was assessed with the Randot Preschool Stereotest[36] and the Worth 4 Dot test,[37] to provide a composite binocular function score that allows grading across a wide range of binocularity.[38] In brief, the binocular function score was derived using the log of the best stereoacuity level identified with the Randot Test (range 40 to 800 arc sec; with corresponding log values of 1.6 to 2.9), administered and scored according to the manufacturer's instructions. In children with no measurable stereoacuity, the Worth 4 Dot test, tested at 6 m (1 degree lights) and 33 cm (6 degree lights), was used to indicate the presence or absence of central and peripheral fusion. Where there was no suppression on the distance Worth 4 Dot test (i.e. they reported 4 lights), a binocular function score of 4 was recorded, and the near response was not assessed. If there was suppression on both the distance and near Worth 4 Dot test (reported only 2 red or 3 green lights), a binocular function score of 5 was recorded.[38]

## Procedure

The children completed the computer-based tasks in the single assessment session, conducted in a quiet, dimly lit room. All tests were assessed binocularly using the child's habitual refractive correction, if worn, and with regular rests provided.

**Useful Field of View Test.** Central and peripheral visual attention and processing were assessed using a computer-based UFOV test (version 7.03; Visual Awareness Research Group, www.visualawareness.com). The test assesses visual processing with increasingly complex tasks that require detection, identification, and localization of briefly presented central and peripheral targets (Fig. 1). Three subtests were conducted to determine the speed of visual processing for: (i) central processing (subtest 1), identification of a central target (a truck or car) presented in a fixation box in the center of the screen; (ii) divided attention (subtest 2), identification of the central target and simultaneous localization of a peripheral target (around 9 degrees from fixation); and (iii) selective attention (subtest 3), the central identification task with localization of a peripheral target embedded in an array of distractors.

These tests were conducted on a standard computer monitor (51 cm × 29 cm) at a working distance of 50 cm. Children used a hand-held mouse to indicate the location of the targets after each presentation. The high-contrast white targets subtend 100 minutes of arc (around 6/120 or 20/400 Snellen visual acuity) presented against a black background. Presentation times range from 16.7 to 500 milliseconds (ms), and processing speed was calculated as the minimum presentation time at which participants accurately performed the task 75% of the time.

**Trail Making Tests.** A custom-written computer-based version of the TMT was developed to assess visual search, attention, and processing speeds, with increasing complexity of tests allowing investigation of the impact of greater cognitive load on test performance (Fig. 2). The test comprises two versions: part A (TMT-A) and part B (TMT-B), based on the widely used paper-based versions. TMT-A involves connecting in numeric order a series of randomly located circles containing numbers (1-2-3…19), as quickly as possible, and provides an estimate of attention and psychomotor speed. Two versions of the TMT-A were conducted: (i) a static version, where the circles remain in the same position during the test; and (ii) a dynamic version, where the remaining circles in the sequence are shifted to different positions after each click, to remove any memory effect. The TMT-B involves connecting a series of randomly located circles containing numbers or letters in alternating order (1-A-2-B…10), as quickly as possible, and requires the use of additional executive function processing during the visual search task. A static and dynamic version of the TMT-B was also conducted, similar to the TMT-A. The children completed the four TMTs in the following order, with increasing complexity: Static TMT-A, Dynamic TMT-A, Static TMT-B, and Dynamic TMT-B. Before each subtest, a short practice test was administered to ensure that the child understood the test.

These tests were conducted on a computer monitor (29.5 cm × 16.5 cm) at a working distance of 43 cm. The high-contrast black optotypes subtend 48 minutes or arc (around 6/60 or 20/200 Snellen equivalent), presented against a white background. For each task, the sequence of connections progressed only when the correct selection was made by the child using a hand-held mouse. The recorded outcome was the response time to successfully complete each sequence (in seconds).

**Statistical Analysis.** All statistical analyses were performed using SPSS (version 25.0, IBM Corp., Armonk, NY) and $P < 0.05$ was considered significant. Parametric and nonparametric tests were used to assess group differences in demographic and visual characteristics.

To investigate the group differences in performance for the UFOV, and TMT outcome measures, linear mixed models (LMMs) were performed using maximum likelihood estimation, with random intercepts for participants to account

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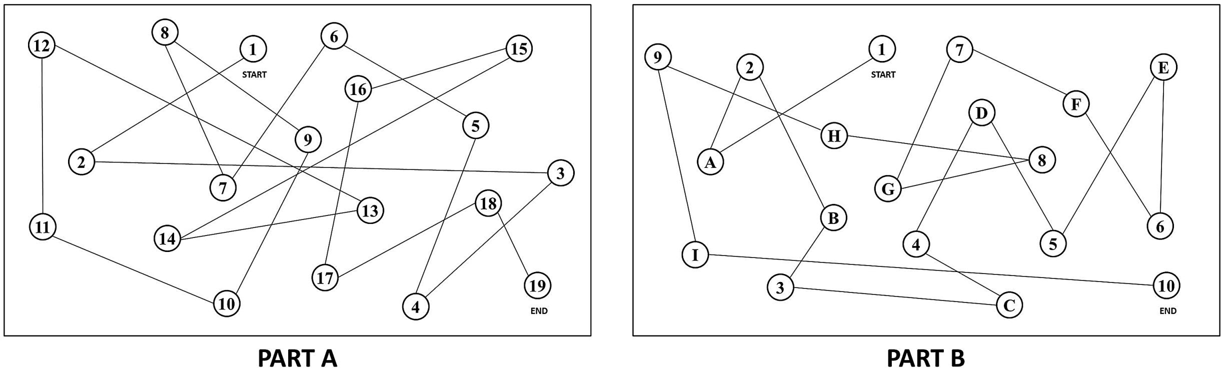


**Figure 2.** Schematic of the Trail Making Test (TMT) tasks: part A (*left*) requires connecting numbers in sequence, in a static and dynamic version; part B (*right*) requires connecting alternating numbers and alphabet letters in sequence, in a static and dynamic version.

**Table.** Visual Function of the Amblyopia ($n = 20$) and Control ($n = 20$) Groups

| Vision Function Tests | Amblyopes Mean (SD) | Controls Mean (SD) | Statistic; *P* Value[†] |
|---|---|---|---|
| Visual acuity, binocular, logMAR | −0.07 (0.10) | −0.17 (0.09) | t(38) = 3.44; $P = 0.001$[*] |
| Visual acuity, better-eye, logMAR | −0.04 (0.09) | −0.13 (0.07) | t(38) = 3.30; $P = 0.002$[*] |
| Visual acuity, worse-eye, logMAR | 0.37 (0.15) | −0.07 (0.07) | t(38) = 12.0; $P < 0.001$[*] |
| Inter ocular difference, logMAR | 0.41 (0.16) | 0.06 (0.04) | t(38) = 9.33; $P < 0.001$[*] |
| Binocular function score, log stereoacuity | 3.06 (1.18) | 1.60 (0.00) | U = 10.0; $P < 0.001$[*] |

[*] $P < 0.05$.
[†] Independent *t*-tests or Mann-Whitney *U* test.

for the repeated measurements. The UFOV model included fixed factors for task difficulty (3 levels: subtests 1, 2, and 3) and group (2 levels: amblyopes versus controls), as well as an interaction term. The TMT models included fixed factors for test type (2 levels: A versus B), task difficulty (2 levels: static versus dynamic mode), and group (2 levels: amblyopes versus controls), as well as all interaction terms. Significant main effects were explored using post hoc analysis with Bonferroni adjustment, and significant interactions were further tested to understand the nature and direction of these relationships.

To assess the contributions of visual function measures on UFOV performance, separate LMM analysis was performed for each visual function measure (binocular VA, better-eye VA, worse-eye VA, interocular difference in VA, and binocular function score). These models included fixed effects of task difficulty (subtests 1, 2, and 3) and random intercepts for participants and maximum likelihood estimation. Similar analyses were performed to assess the contribution of visual function on TMT performance. These models included fixed effects of test type (2 levels: A versus B), task difficulty (2 levels: static versus dynamic mode), with random intercepts for participants. All models were age-adjusted to minimize any potential confounding effects of age-related variations in visual function.

## Results

The total sample included 20 children with amblyopia (mean age = 9.0 ± 1.2 years; 15 anisometropic and 5 strabismic) and an age-similar group of 20 children with normal vision (9.5 ± 1.7 years). All children were carried in full-term pregnancies (37+ weeks gestation) and from parent report had no known neurological, intellectual, or ocular disorders (other than their refractive error or their amblyogenic conditions). There was no significant difference in age between the children with amblyopia or the controls (t(38) = −1.0; $P = 0.32$). All children were able to successfully complete the visual function tests, as well as the visual search and attention tests, within a 30-minute test session, inclusive of rest breaks. The children with amblyopia demonstrated reduced acuity and poorer binocular function under all viewing conditions compared to the control children ($P < 0.002$; Table). Eight children with amblyopia had no measurable stereoacuity, five of whom exhibited central fusion on the distance Worth 4 Dot test, whereas three exhibited suppression, both at distance and near (see Supplementary File).

Mean visual processing speed for the three UFOV subtests for the children with amblyopia and controls are summarized in Figure 3. Overall, across all three test variations, children with amblyopia exhibited significantly slower visual processing speeds compared to controls (65.0 vs. 37.0 ms, $F(1,40) = 4.51$, $P = 0.04$). For all children, increasing task difficulty was significantly associated with slower visual processing speeds ($F(2, 80) = 30.34$, $P < 0.001$). In the post hoc comparisons, there was no significant difference between subtest 1 and 2 ($P = 0.06$), but there were significant differences between subtests 1 and 3 ($P < 0.001$), and subtests 2 and 3 ($P < 0.001$). There was no significant interaction effect between group and task difficulty ($F(2,80) = 2.81$, $P = 0.07$), but there was a trend towards slower visual processing speeds in the children with amblyopia relative to the controls with increasing task difficulty.

Mean completion times for the TMT A and B tests, for the static and dynamic mode, in the children with amblyopia and controls are summarized in Figure 4. Overall, the children with amblyopia took significantly longer to complete the tests compared with controls (76.8 vs. 58.0 seconds; $F(1,40) = 6.64$, $P = 0.014$), as well as a significant interaction

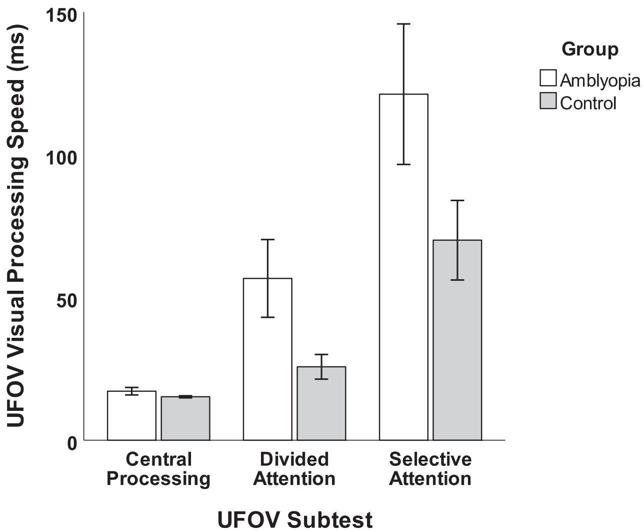


**Figure 3.** Mean (±1 SEM) visual processing speed as a function of the Useful Field of View (UFOV) subtests for the amblyopic and control children.

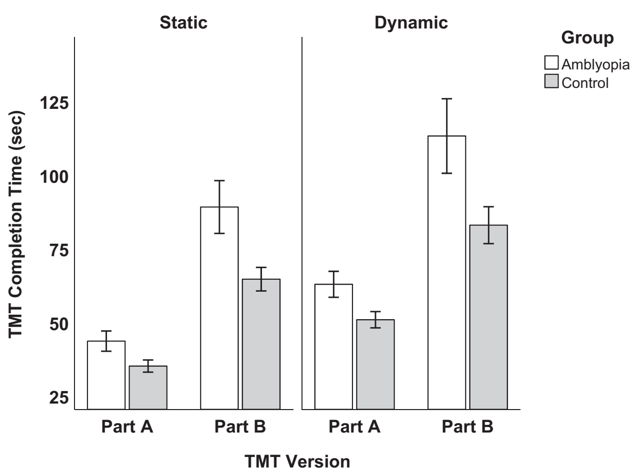


**Figure 4.** Mean (±1 SEM) Trail Making Test (TMT) completion time (seconds) for TMT-A and TMT-B for the static (*left*) and dynamic (*right*) versions for the amblyopic and control children.

between group and TMT test type ($F(1,120) = 8.1$, $P = 0.005$). Across all test variations, completion times were significantly longer for the TMT-B compared to the TMT-A (87.0 vs. 47.7 seconds, $F(1,120) = 171.3$, $P < 0.001$), and were longer when presented in the dynamic compared to the static mode (77.0 vs. 57.7 sec, $F(1,120) = 41.5$, $P < 0.001$). In the simple effects models, this interaction showed a stronger detrimental impact of amblyopia on TMT-B performance ($F(1,40) = 6.13$, $P = 0.016$) compared to TMT-A performance ($F(1,40) = 5.79$, $P = 0.021$). There were no other significant two-way or three-way interaction effects, indicating that amblyopia did not differentially impact on performance for the dynamic compared to static versions.

Analyses also explored the contribution of each visual function measure on visual attention and search performance of all children, adjusting for task difficulty and age. The association between binocular VA and UFOV performance approached significance ($P = 0.06$), whereas the remaining variables were not significant (better-eye VA $P = 0.33$; worse-eye VA $P = 0.15$; inter-ocular difference $P = 0.20$; and binocular function score $P = 0.21$). Binocular VA was a significant predictor of TMT performance ($F(1,40) = 8.47$, $P = 0.006$), with a 1-line reduction in VA (0.10 logMAR) associated with longer TMT completion times (8.6 seconds; 95% confidence interval [CI] 2.6 to 14.6 seconds). Better-eye VA was also a significant predictor of TMT performance ($P = 0.046$), yet none of the other vision variables were significant (worse-eye VA $P = 0.07$; inter-ocular difference $P = 0.18$; and binocular function score $P = 0.07$).

## Discussion

This study demonstrated that performance on several tests that involve higher order visual processing and executive function were poorer in children with amblyopia than those with normal vision, even when viewed binocularly. In particular, children with amblyopia demonstrated slower visual processing speeds on the divided and selective-attention UFOV tasks, and slower completion times on the TMT visual search tasks, particularly for the TMT-B, which involves higher levels of executive function. Although these tasks are visually guided, performance was not strongly associated with clinical measures of visual function. None of the VA or binocular function measures were significantly related to UFOV performance and only reduced binocular VA was associated with slower completion times on the TMT. Interestingly, TMT times were not related to VA in the worse eye or binocular function, which are the vision measures that clinically describe severity of amblyopia.

Whereas previous studies report that adults with amblyopia have longer response times for visual search tasks, when the task is viewed by the amblyopic eye,[21–24] this study is the first to highlight the impact of amblyopia on binocular visual attention and visual search. This finding demonstrates deficits in higher order visual processing in children with amblyopia, beyond reduced visual acuity and loss of binocular function that clinically define the condition. These findings also add to the evidence for the impact of amblyopia on higher-order visual processing previously reported, such as losses in detection of stimuli defined by modulations in contrast or texture (second-order detection), global form and motion integration, attentional blink (inability to detect a second target shown shortly after the first presented in rapid sequence), symmetry detection and counting[22,23] (see review by Levi 2006[39]).

Furthermore, our finding of reduced binocular visual attention and search performance in children with amblyopia for more cognitively demanding tasks, suggests that the negative effects of amblyopia may be exacerbated when undertaking more complex visually directed everyday activities. This adds to the growing literature on the binocular performance deficits of children with amblyopia, such as reading,[7,8] writing,[11] and manual dexterity tasks,[9,10] particularly when these performance measures are timed.

Our findings provide evidence of attentional deficits in childhood amblyopia, which have also been previously demonstrated in hyperopic children aged 6 to 7 years, irrespective of spectacle correction use.[26] Attentional deficits have been reported as part of a cluster that includes spatial cognition, visuomotor coordination, and visual motion and stereo processing, which are all functions that are associated with the dorsal stream.[40] A broad vulnerability in the dorsal stream of the visual pathway has been proposed to underlie the global motion, visuo-motor, and attentional deficits that underpin visual control of actions.[41] These higher-order deficits identified in this study may contribute to the poorer fine motor skills previously reported in children with amblyopia, which have not been found to be strongly associated with the clinical vision measures that define the condition.[10,17] Future studies are needed to explore the underlying neural substrates affected by amblyopia in a child's developing brain networks.

Novel and emerging active treatments for amblyopia include dichoptic training, performing perceptual learning tasks, or playing action video games.[29] However, whereas understanding of the mechanisms underlying improvements in functional performance from these treatments is limited, it has been suggested that associated improvements in higher order global visual attention may play a role.[29] Dichoptic training presents concurrent visual activity to both the amblyopic and fellow eye, by varying the relative contrast of visual targets to promote simultaneous binocular perception (that is, reduce interocular suppression).[42–44] Although some studies report that visual acuity, binocular function, and binocularly performed timed manual dexterity proficiency all improve following relatively short durations of dichoptic treatment,[27,28,43] other randomized controlled treatment trials have not shown significant improvements in VA with home-based dichoptic therapy.[45,46] Variable adherence to therapy has been speculated as a potential source of difference between studies and individual variability in responses to therapy within studies.[47,48] Perceptual learning describes the improvement on a sensory task by repeated practice, and has been shown to transfer to improvements in other aspects of visual function, which is suggested to be from higher-order cognitive learning.[49] Interestingly, there is little difference in VA outcomes among the active amblyopia treatment methods, implying that improvement to some extent may ensue, as long as the amblyopic eye is given opportunity to engage, either on its own or simultaneously, with the dominant eye. Action video gaming has also been shown to alter a range of visual skills in visually normal adults, including VA, stereoacuity, and different aspects of visual attention, including UFOV and attentional blink.[50] Potentially, targeting the higher-order visual attention processes may be driving the success seen in older children and adults in emerging active amblyopia treatment methods.[29]

The interpretation of our findings may be subject to several limitations. First, the small sample size reduced the statistical power to explore whether any differences in performance varied between strabismic and anisometropic amblyopes and should be explored in future research. In addition, although this study focused on exploring group differences on tests of visual attention and visual search, it did not include any assessments of other functional tasks, such as reading, motor skill proficiency, and patient-reported outcomes of function. Therefore, future research should explore the associations between deficits in binocular visual attention and visual search skills and performance on functional everyday activities.

In conclusion, this study demonstrated that children with amblyopia exhibit deficits in the higher-order visual processing skills of visual attention and visual search involving different levels of executive function under binocular viewing conditions. These deficits have clear implications for the impact of amblyopia on everyday function for children and may underlie the reported performance reductions in reading, fine motor skills and visuomotor proficiency.


## *Acknowledgments*

Disclosure: **A.A. Black,** None; **J.M. Wood,** None; **S. Hoang,** None; **E. Thomas,** None; **A.L. Webber,** None


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