Research in Developmental Disabilities 131 (2022) 104364

Contents lists available at ScienceDirect

Research in Developmental Disabilities

journal homepage: www.elsevier.com/locate/redevdis

# Assessing visuospatial processing in cerebral visual impairment using a novel and naturalistic static visual search task

Xin Zhang[a,1], Claire E. Manley[a,1], Serena Micheletti[b], Isidora Tesic[c], Christopher R. Bennett[a], Elisa M. Fazzi[b,c], Lotfi B. Merabet[a,*]

[a] *The Laboratory for Visual Neuroplasticity, Department of Ophthalmology, Massachusetts Eye and Ear, Harvard Medical School, Boston, USA*
[b] *Unit of Child Neurology and Psychiatry, ASST Spedali Civili of Brescia, Brescia, Italy*
[c] *Department of Clinical and Experimental Sciences, University of Brescia, Brescia, Italy*

## ARTICLE INFO

*Keywords:*
Cerebral visual impairment (CVI)
Visual search
Eye tracking
Visual processing deficits
Attention
Visual perception

## ABSTRACT

*Background:* Cerebral visual impairment (CVI) is a brain based visual disorder associated with the maldevelopment of central visual pathways. Individuals with CVI often report difficulties finding a target of interest in cluttered and crowded visual scenes. However, it remains unknown how manipulating task demands and other environmental factors influence visual search performance in this population.

*Aim:* We developed a novel and naturalistic virtual reality (VR) based static visual search task combined with eye tracking called the “virtual toy box” to objectively assess visual search performance in CVI.

*Methods and procedures:* A total of 38 individuals with CVI (mean age 13.18 years ± 3.58 SD) and 53 controls with neurotypical development (mean age 15.25 years ± 5.72 SD) participated in the study. In a first experiment, study subjects were instructed to search for a preselected toy presented among a varying number of surrounding distractor toys (set size ranging from 1 to 36 items). In a second experiment, we assessed the effects of manipulating item spacing and the size of the visual area explored (field of view; FOV).

*Outcomes and results:* Behavioral outcomes collected were success rate, reaction time, gaze error, visual search area, and off-screen percent (an index of task compliance). Compared to age-matched controls, participants with CVI showed an overall impairment with respect to all the visual search outcomes of interest. Specifically, individuals with CVI were less likely and took longer to find the target, and search patterns were less accurate and precise compared to controls. Visual search response profiles were also comparatively less efficient and were associated with a slower initial pre-search (visual orienting) response as indexed by higher slope and intercept values derived from the analysis of reaction time × set size functions. Search performance was also more negatively affected in CVI at the smallest as well as largest spacing conditions tested, while increasing FOV was associated with greater decreased gaze accuracy and precision

*Conclusions and implications:* These results are consistent with a general profile of impaired visual search abilities in CVI as well as worsening performance with increased visual task demands and an overall sensitivity to visual clutter and crowding. The observed profile of impaired visual search performance may be associated with dysfunctions related to how visual selective attention is deployed in individuals with CVI.

---

[*] Correspondence to: Ophthalmology, Massachusetts Eye and Ear, Harvard Medical School, 20 Staniford Street, Boston, MA 02114, USA.
*E-mail address:* lotfi_merabet@meei.harvard.edu (L.B. Merabet).

[1] Equal Contributing Authors.

https://doi.org/10.1016/j.ridd.2022.104364
Received 7 January 2022; Received in revised form 15 July 2022; Accepted 10 October 2022

## 1. Introduction

Visual search describes the ability to find a particular target in the environment, distinguish it from other items, and ignore irrelevant surrounding information (Eckstein, 2011; Wolfe, 2020). While seemingly effortless, visual search is nonetheless a complex neurophysiological process that requires the coordinated movement of not only the eyes, but also neural signaling between multiple structures and regions of the brain (Johnson et al., 2016). Previous experimental work has shown that visual search performance serves as an important proxy for visuospatial information processing abilities and the deployment of attentional resources (Treisman & Gelade, 1980). It is also useful in evaluating functional vision abilities. That is, how an individual uses their vision to perceive and interact with their surroundings (Bennett et al., 2019; Colenbrander, 2005).

Visual search becomes more efficient with age and by 11–12 years, performance levels appear comparable to that of adults (Gil-Gomez de Liano et al., 2020). However, in the case of children with neurodevelopmental disorders or early neurological injury, this trajectory is much more complex. Cerebral visual impairment (CVI) is a heterogeneous brain based visual disorder that has been defined as “verifiable visual dysfunction associated with damage to retrochiasmatic pathways and cerebral structures that cannot be attributed to disorders of the anterior visual pathways or potentially co-occurring ocular pathology” (Sakki et al., 2018). Common causes of CVI include hypoxic-ischemic injury, trauma, infection, as well as genetic and metabolic disorders (Fazzi et al., 2007; Hoyt, 2003). Pre, post, or peri-natal neurological injury is believed to lead to the maldevelopment and malfunction of key visual processing structures and pathways (Volpe, 2009).

Individuals with CVI present with a broad range of visual deficits including reduced visual acuity, visual field defects, reduced contrast sensitivity, and ocular motor abnormalities (including the ability to maintain fixation as well as initiate saccades and maintain pursuit movements) (Fazzi et al., 2007; Philip & Dutton, 2014). Interestingly, higher order visual perceptual deficits associated with visuospatial processing and attention are also commonly present, even in cases when measures of visual function (i.e. visual acuity and perimetry) are within normal or near normal levels (Boot et al., 2010; Dutton, 2013; Dutton et al., 2006). Indeed, individuals with CVI often report feeling highly anxious in crowded environments and overwhelmed when viewing complex visual scenes (Jacobson et al., 1996; Lam et al., 2010; McDowell & Dutton, 2019). Despite having intact visual field function, they may perceive only a very small area of space at a time (Philip & Dutton, 2014). For example, a child with CVI may have difficulties finding their favorite toy when placed in a box filled with other toys, despite being able to identify the same toy when presented in isolation (Bennett et al., 2018; McKillop & Dutton, 2008). This is in line with previous observations suggesting that individuals with CVI have difficulties with searching and extracting visual information in cluttered visual scenes (Dutton et al., 2004). In turn, these perceptual dysfunctions can have a negative impact on development and functional independence (Boot et al., 2010; Dutton, 2013; McKillop & Dutton, 2008). However, more objective studies are needed to characterize the nature and factors that exacerbate these visual perceptual difficulties in CVI.

Depending on regional practices, visual dysfunctions related to higher order visual processing are not typically evaluated as part of a standard ophthalmological exam (van Genderen et al., 2012; Williams et al., 2011). Visual perceptual abilities can be assessed by neuropsychological testing (e.g., Developmental Test for Visual Perception). However, a number of factors may potentially bias testing results including the need for verbal and/or manual motor responses, sufficient visual acuity to view fine detailed images, and comprehension of task requirements. In contrast, objective tests of visual function (such as visual acuity) are usually carried out using simple letter optotypes and targets on uniform backgrounds that do not capture the complexity and perceptual demands of natural visual scenes. In considering these issues, it remains difficult to disentangle the nature of visual perceptual deficits observed in CVI. There is thus a need to develop novel and objective assessment tools that can help characterize higher order perceptual processing abilities in relation to everyday activities, allow for the controlled examination of various factors such as task demands and image complexity, and possibly identify adaptive strategies that could be transferred to real world situations (Kran & Mayer, 2011; McDowell, 2020; Merabet et al., 2017). These novel assessment approaches should be behaviorally relevant by simulating a task an individual with CVI may encounter so as to assess how they use their vision in real world situations (i.e., functional vision abilities (Colenbrander, 2005)) while promoting a high level of testing compliance and engagement (Bennett et al., 2018; McDowell, 2020; Williams et al., 2011). Failing to fully characterize these visual perceptual impairments in CVI can lead to an underestimation of an individual’s true clinical profile, and in turn deny them appropriate accommodations to address their specific needs (McConnell et al., 2021; McDowell, 2020; Merabet et al., 2017).

In a preliminary study, we investigated visual search behavior in individuals with CVI using a novel virtual reality (VR) based task called the “virtual toy box” (Bennett et al., 2018). This simulated the visual search of a fixed number of static items within a naturalistic and intuitive visual environment. Using an eye tracker to capture gaze behavior, we found that participants with CVI (mean age 18.7 years) showed qualitatively greater variability in their search patterns along with a trend of longer reaction times in finding a target with increasing task complexity (i.e. as defined by varying the number of unique surrounding distractors) compared to individuals with an ocular based impairment as well as controls with neurotypical development (Bennett et al., 2018). In the current study, we built upon these early findings by investigating the effect of manipulating task parameters on performance including varying the search set size (i.e., number of surrounding distractors) as well as the spacing between objects and field of view (FOV) of the search area explored. We captured multiple performance outcomes including success rate and reaction time, as well as gaze error and visual search area (as indices of gaze accuracy and precision, respectively) and off-screen percentages (an index of task compliance). We also employed behavioral analysis approaches that are well characterized in the visual search literature. For example, the linear slope computed from a reaction time × set size function is considered to be an index of visual search efficiency and reflects the cost of each additional distractor element in terms of reaction time. The derived y intercept value corresponds to the initial perceptual processing (pre-search) response time and is influenced by non-search task components (Wolfe, 2016; Wolfe et al., 2002). While visual search is inherently a complex and intertwined process, it is conceptually useful to separate slope and intercept values as measures of attentional and pre-attentive perceptual processes respectively (Joseph et al., 2009). To our knowledge, this type of analysis has not been previously used to characterize visual search performance in CVI.

In experiment 1, we investigated the effect of varying the number of surrounding distractors (set size) on visual search performance in participants with CVI compared to chronologically age-matched controls with neurotypical development. We hypothesized that as a group, participants with CVI would show a general impairment in performance compared to controls with respect to all behavioral outcomes. Furthermore, visual search response profiles in CVI would be consistent with reduced efficiency as indexed by an increase in the slope value derived from the reaction time × set size function. In experiment 2, we investigated visual search performance as a function of varying the spacing between distractor elements in the array, as well as the size of the visual area explored (field of view; FOV). Consistent with previous clinical accounts, we hypothesized that CVI participants would show the greatest impairment in visual search performance at the smallest distractor spacing size. In other words, when items were closest together and the search array appearing the most crowded. In contrast to the effect of smallest spacing, impairments in visual search would be most evident at the largest FOV size. That is, searching for items distributed across larger viewing areas would also lead to a greater impairment in visual search performance.

## 2. Methods

### 2.1. Study participants

A total of 91 individuals participated in the study, with roughly an equal distribution of experimental and control subjects between the two experiments (experiment 1: n = 47; controls = 25, CVI = 22 and experiment 2: n = 44; controls = 28, CVI = 16).

Thirty-eight (38) participants previously diagnosed with CVI and aged between 7 and 20 years old (mean age 13.18 years ± 3.58 SD; 28 males) were enrolled in the study. Fifty-three (53) participants with neurotypical development aged between 6 and 26 years old (mean age 15.25 years ± 5.72 SD; 29 males) served as comparative controls. Control participants had normal or corrected to normal visual acuity and no previous history of any ophthalmic (e.g. strabismus, amblyopia) or neurodevelopmental (e.g. attention deficit hyperactivity disorder) conditions. Recruitment was designed to be as inclusive as possible while maintaining inclusion/exclusion criteria to promote the capture of high-quality data. Furthermore, with the age range of this cohort, visual functional abilities, visual search performance and other neurophysiological changes are likely to have stabilized, thus mitigating possible developmental confounds in relation our behavioral outcomes.

Participants with CVI were all previously diagnosed by experienced clinicians specializing in neuro-ophthalmic pediatric care. Diagnosis was based on a directed and objective assessment of visual functions (e.g., visual acuity, contrast, visual field perimetry, color, and ocular motor functions), thorough refractive and ocular examination, as well as extensive and integrated review of medical (including developmental, birth, and gestational) history, as well as neuroimaging and electrophysiology records (Chandna et al., 2021). Further input regarding visual behaviors obtained from available questionnaires and inventories (McCulloch et al., 2007; Ortibus et al., 2011) were also collected and reviewed for the purposes of formalizing the diagnosis (Kran et al., 2019).

All participants with CVI had visual impairments (e.g., reduced visual acuity, contrast, ocular motor function, and self-reported perceptual dysfunctions) related to pre- or perinatal neurological injury and/or neurodevelopmental disorders. The majority were associated with preterm (i.e. born < 37 weeks gestation; 68.18 %) compared to term (31.84 %) birth. Causes of CVI included hypoxic-ischemic injury related to prematurity (including periventricular leukomalacia; PVL), hypoxic/ischemic encephalopathy (HIE), as well as genetic disorders. Associated neurodevelopmental comorbidities included spastic and dystonic cerebral palsy. Best corrected visual acuities in the better seeing eye ranged from 7/10 to 10/10 (Snellen equivalent; 0.2–0.0 logMAR equivalent). All participants had visual acuities, intact visual field function within the area corresponding to the visual stimulus presentation, as well as fixation and ocular motor function sufficient for the purposes of completing the task requirements (see below for details regarding eye tracking calibration and visual stimulus size). Exclusion criteria included any evidence of oculomotor apraxia, intraocular pathology (other than mild optic atrophy), visual field deficit corresponding to the area of visual testing, uncontrolled epilepsy seizures, as well as cognitive deficit precluding the participant from understanding the requirements of the study and offering consent/assent. Participants with CVI were also categorized according to criteria developed by Dutton and Lueck (2015). In this study sample, the distribution of CVI participants was limited to categories 2 and 3 (category 2: 68.18 % defined as “have functionally useful vision and cognitive challenges” and category 3: 31.81 % defined as “functionally useful vision and who can work at or near expected academic level for their age group”).

Across both experiments, comparing CVI participants and controls revealed no statistically significant difference with respect to age (compare CVI: 13.18 years ± 3.58 SD and controls: 15.25 years ± 5.72 SD; p = 0.51). However, the groups were statistically different with respect to verbal intelligence quotient (compare CVI: 92.31 ± 20.87 SD and controls: 108.68 ± 11.78 SD; p = 0.01; Wechsler Intelligence Scale for Children, 4th Edition).

Written informed consent was obtained from all participants and a parent/legal guardian (in the case of a minor) prior to commencing the study. The study was approved by the Investigative Review Board at the Massachusetts Eye and Ear in Boston, MA, USA and carried out in accordance to the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans.

### 2.2. Behavioral task and visual stimulus design

As part of an ongoing study directed at characterizing visuospatial abilities in CVI, we developed a desktop VR static object based visual search task referred to as the "virtual toy box" which was modified for the specific aims of this study (see Bennett et al., 2018 for details regarding initial focus group work and preliminary results). Briefly, the behavioral task represents a simulated rendering of a toy box with an array of static toys shown in canonical view and without overlap. The task is presented in a trial-by-trial fashion, and viewed from an overhead, first-person perspective. Prior to commencing the study, participants were instructed to select a target toy presented in isolation and rotating around the y axis. The options were a yellow duck, orange basketball, and blue truck. This was done to confirm that the participant could identify the search target in isolation, as well as promote engagement and enhance the immersive feel of the task. Once selected, participants were instructed to search, locate, and fixate a specific target toy placed in a random location among a heterogeneous array of surrounding distractor toys (selected from a pool of 42 possible items; Fig. 1 A. See below for task design details for each experiment). The target toy remained constant and was completely unique in terms of shape and features in order to create a "pop out" target effect (akin to a feature based visual search) when presented with the other distractor toys. The target toys never appeared as distractors, however the colors used in the design of the toys could be repeated. The visual environment was developed using the Unity 3D game engine (Unity Technologies; version 5.6) and in-house 3D object models were created using Blender modeling software (Blender Foundation).

Participants were seated comfortably in a quiet room (to minimize distractions) and in front of a laptop computer with the eye tracker mounted on the lower portion of the monitor (HP Zbook 17 Mobile Workstation; LED backlit monitor (38 cm × 21 cm; contrast ratio: 300:1; refresh rate: 60 Hz; resolution: 1600 × 900; viewing distance of 57 cm). Eye movement patterns during visual search (i.e. X,Y coordinate positions of gaze) were captured under binocular viewing conditions using a Tobii 4 C Eye Tracker system (90 Hz sampling frequency, Tobii Technology AB, Stockholm, Sweden). Participants were reminded to maintain their gaze on the monitor during testing but were otherwise able to move their head freely. Eye tracking calibration was performed (Tobii Eye Tracking Software, v 2.9 calibration protocol) using a 7-point calibration task (screen positions: top-left, top-center, top-right, bottom-left, bottom-center, bottom-right, and center-center; each fixation target presentation: 3 s) followed by a 9-point post calibration verification (the same 7-point calibration points plus a center-left and center-right position). Accuracy criterion was defined by gaze fixation falling within a 2.25 arc degree radius around each of the 9 screen positions and confirmed by visual inspection.

#### 2.2.1. Experiment 1. Effect of varying set size

Prior to commencing data collection, participants were shown 2–3 practice examples of the toy box scene to confirm their understanding of the task requirements. For the experiment, the preselected target toy was placed in a random location either in isolation or in the presence of a varying a specific number of surrounding distractors (5, 15, 20, 25, 30, and 35) corresponding to a set size ranging from 1 to 36 items (Fig. 1 B). The size of the toys and the spacing between them remained constant throughout all trials. The location of the target and surrounding distractors were randomized on each trial, and the number of trials for each possible set size was presented equally and in a random order. A trial consisted of 3 s viewing the toy box scene followed by a 1 s blank grey screen with a central fixation target. This was repeated 50 times per run and data from 3 runs were collected (i.e. 3 × 50 trial blocks for a total of 150 trials). Each run lasted 3.5 min, with a brief rest period in between. Total testing time was approximately 15–20 min for each

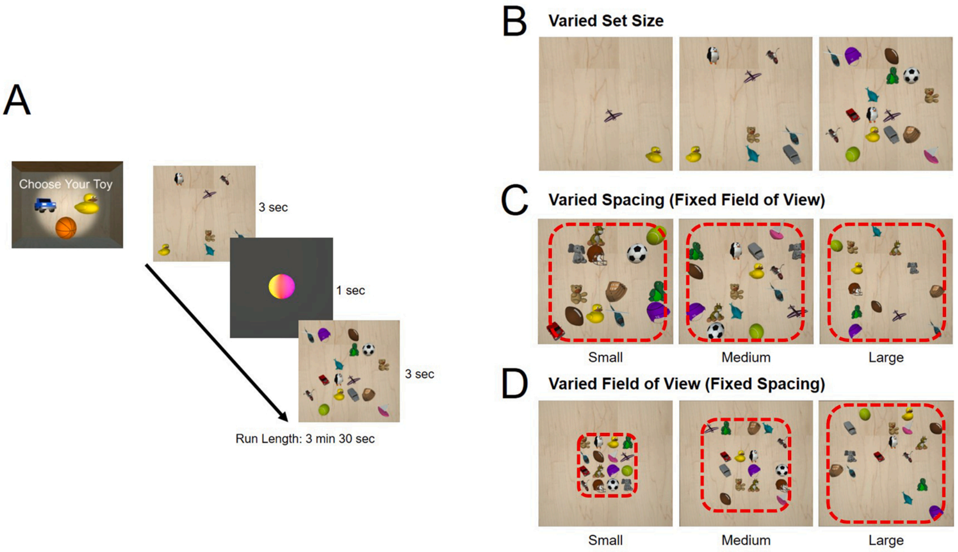

**Fig. 1.** Experimental design. A) The selected search toy (in this case, a yellow duck) was placed in different locations within an array of distractor toys. Experiment 1 investigated the effect of varying (B) the number of distractors (set size). In experiment 2, the effect of varying (C) spacing between elements and (D) visual search area (field of view; FOV) were assessed.

participant. At a viewing distance of 57 cm, the virtual toy box subtended 17° × 17° of visual angle in a maximum grid array of 6 × 6 elements. The toys subtended 1.0–1.2° of visual angle in both dimensions.

### 2.2.2. *Experiment 2. Effect of varying spacing and field of view*

In second set of experiments, we assessed the effect of varying set size while manipulating the spacing between items and the size of visual search area explored (field of view; FOV). For spacing, the design parameters used in experiment 1 were replicated to generate a "medium" distance spacing condition. Then, spacing between objects was reduced by 75 % (small spacing condition) and increased by 125 % (large spacing condition). This generated 3 spacing conditions, while maintaining a fixed FOV. Note that in order to maintain the fixed FOV, the relative size of the targets was proportionally increased and decreased (Fig. 1 B). At a viewing distance of 57 cm, the virtual toy box subtended 17° × 17° of visual angle and inter-item spacing varied from 0.75°, 1°, and 1.25° (for small, medium and large spacing respectively). The effect of varying FOV was investigated by again using the design parameters corresponding to experiment 1 to generate a "medium" condition. Then, the grid size was reduced 75 % (small FOV) and increased by 125 % (large FOV) to create 3 FOV conditions, while maintaining a fixed object spacing. (Fig. 1 C). At a viewing distance of 57 cm, the virtual toy box subtended 12.75° × 12.75°, 17° × 17°, and 21.25° × 21.25° of visual angle (for small, medium and large FOV respectively).

Following the same task design of experiment 1, each trial consisted of 50 trials each lasting for 3 s followed by a 1 s fixation target, for a total run length of 3.5 min. Each run was repeated 3 times allowing for short breaks in between. The presentation order between the spacing and FOV tasks was counterbalanced across subjects. Total testing time was approximately 30–40 min for each participant.

## 2.3. *Behavioral data capture, outcome measures, and analysis*

Visual search performance was analyzed based on captured eye tracking data while participants initially viewed, searched, located, and then fixated the target. Two primary objective outcomes were collected for this purpose. First, mean success rate (expressed as percent correct responses) was determined based on whether a participant was able to find and fixate the target on a given trial. Successful fixation criterion was defined as sustained gaze remaining within the outer contour of the target for a minimum time of 0.4 s. Second, mean reaction time (expressed in msec) was defined as the first moment gaze arrived within the outer contour of the target, and remained successfully fixated for a minimum of 400 ms (Bennett et al., 2018).

Reaction time data were also used to compute reaction time × set size functions where the slope and intercept values were determined for each individual (Sternberg, 1966). Note that as a validation step, we also determined reaction time for the zero-distractor condition, which was recorded to confirm agreement with the derived intercept value from the reaction time × set size function.

Three other outcomes were analyzed to further characterize visual search performance. Gaze error (expressed in arc degrees) was defined as the distance between the center of the target and participant's gaze position (Bennett et al., 2018). This was calculated based on the sampling rate of the eye tracker (90 Hz) and serves as a measure of target localizing and fixation accuracy (Bennett et al., 2018). Visual search area (expressed as percent of the screen area) was determined based on an ellipse shaped 95 % confidence interval fitted to the captured eye tracking data, representing a measure of visual search precision (Bennett et al., 2018). Finally, we also determined how often/long participants were able to maintain their gaze on the screen based on the continuous recording of gaze coordinate positions. For this purpose, the off-screen count (expressed as a percent) represents the proportion of gaze points that fell outside of the bounds of the screen per trial. This metric serves as an index of testing compliance, reliability, and task engagement (Bennett et al., 2018, 2021).

Statistical analyses were carried out using a multivariate analysis of covariance (MANCOVA) to determine if there was a group effect on overall performance, an effect of spacing and FOV on overall performance, and an interaction effect on overall performance. An analysis of variance (ANOVA) was used to see if there was a group, condition, or interaction effect on each individual performance outcome. Finally, a series of independent sample t-tests (Welch's for unequal variances) were used to investigate between group effects. Effect sizes are reported as Cohen's d and partial eta squared for t-tests and ANOVAs respectively. To determine if visual search outcomes were associated with potential factors of interest, a MANCOVA was conducted with age and verbal IQ as predetermined covariates. All statistical analyses were performed using SPSS Statistics package version 24 (IBM; Armonk, NY) and statistical significance was set at $p < 0.05$.

# 3. Results

## 3.1. *General behavioral results*

All study participants were able to successfully complete the eye tracking calibration procedure and all the possible toy targets were selected by both groups. Overall, the orange basketball appeared as the most chosen target [orange basketball: 42.60 % (controls = 52 %, CVI = 32 %), yellow duck: 34.00 % (controls = 28 %, CVI = 41 %), blue truck: 23.40 % (controls = 20 %, CVI = 27 %)]. However, the observed difference in overall distribution frequency was not statistically significant [$\text{Chi}^2 (2, n = 47) = 1.96, p = 0.38$]. Regarding task compliance, we calculated mean off-screen percentage and found no statistically significant difference between the two groups (compare CVI: 3.01 % ± 0.73 SD and controls 3.34 % ± 0.05 SD) [$t(45) = -1.61, p = 0.122, d = 0.50$]. The relatively low value of off-screen percentage values and comparable performance suggests that both groups maintained a high level of task compliance and engagement.

### 3.2. Experiment 1 – effect of varying set size

We examined the effect of varying the number of distractors (set size) on visual search performance with respect to all the outcomes of interest. In general, the participants in the CVI group showed an overall impairment in visual search compared to controls (Fig. 2). With respect to the primary outcomes of interest, mean success rate for the CVI group (86.05% correct ± 0.09 SD) was lower compared

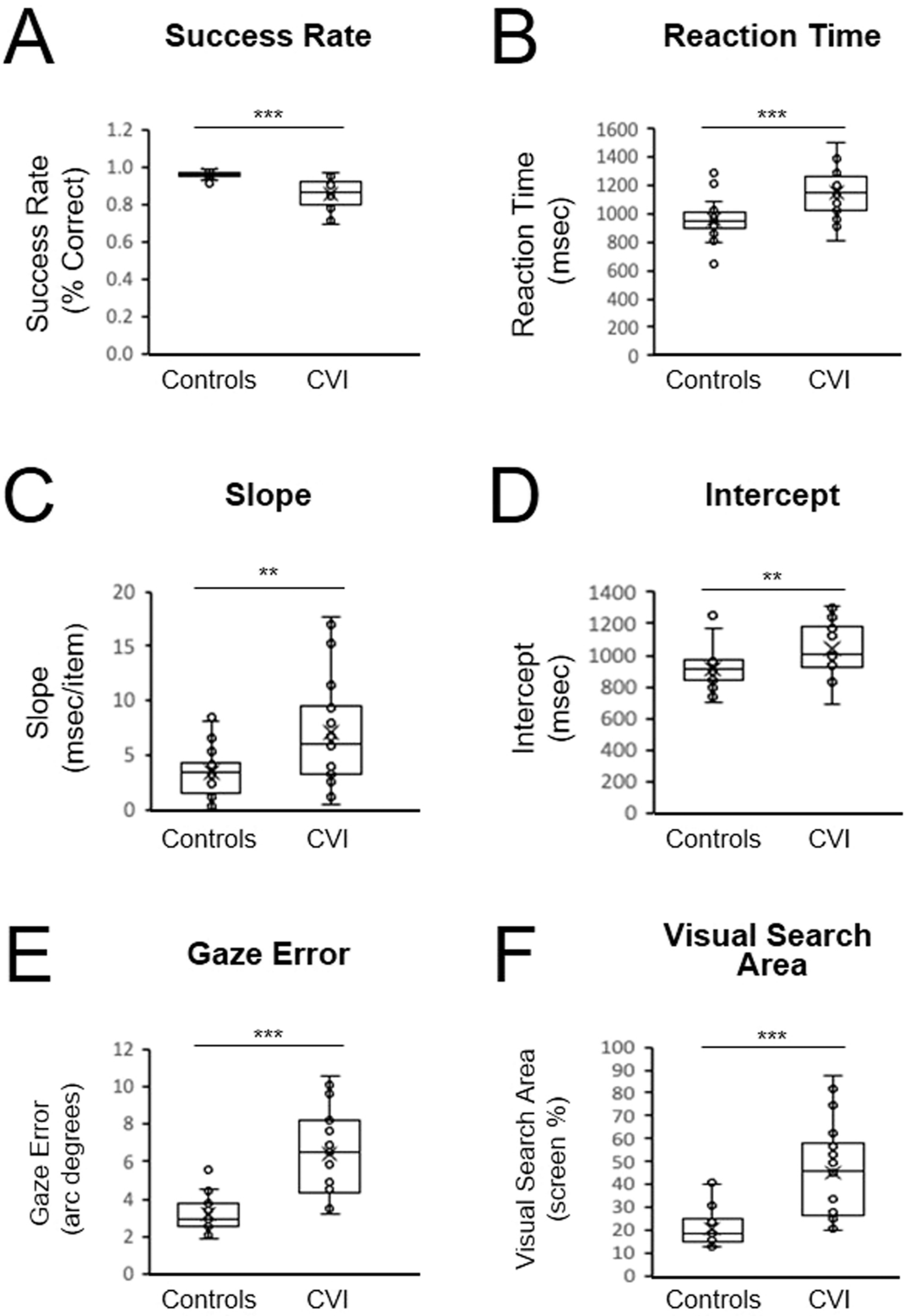

**Fig. 2.** Group comparisons of visual search performance. Compared to controls, CVI participants showed significantly worse performance with respect to A) success rate, B) reaction time, C) mean slope value, D) mean intercept value, E) gaze error, and F) visual search area. Individual values are overlaid on group box plots indicating the mean (X), median, first and third quartiles, as well as minimum and maximum values. Levels of statistical significance: *p < 0.05; **p < 0.01; ***p < 0.001.

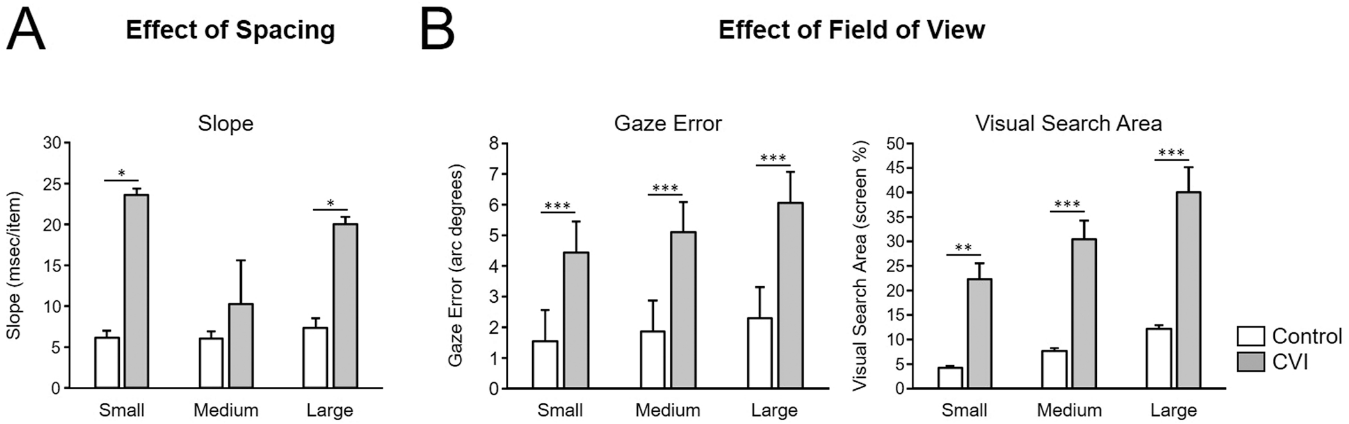

**Fig. 3.** Comparison of visual search profiles by computing performance outcome × set size functions. Compared to controls, CVI participants showed significantly worse performance on A) success rate, B) reaction time, C) gaze error, and D) visual search area with respect to varying set size. Error bars represent ± SEM.

to controls (96.08 % correct ± 0.02 SD) (Fig. 2 A). A t-test comparison confirmed that this difference was statistically significant [t (45) = 5.76, $p < 0.001$, d = 1.79] suggesting that CVI participants were less likely to find the target toy compared to controls. We also found a statistically significant difference with respect to mean reaction time with CVI participants (1145.11 ms ± 164.64 SD) taking longer to find the target compared to controls (960.58 ms ± 126.47 SD) [t(45) = 4.27, $p < 0.001$, d = 1.27] (Fig. 2 B). CVI participants also showed a significantly greater mean slope value (7.05 msec/item ± 4.81 SD) compared to controls (3.33 ms/item ± 2.22 SD) [t(45) = 3.34, $p > 0.01$, d = − 1.02] (Fig. 2 C). The evidence of a higher slope value in CVI is consistent with decreased visual search efficiency compared to controls. We also observed a significantly higher mean intercept value in the CVI group (compare CVI: 1041.23 ms ± 168.71 SD and controls: 916.03 ms ± 117.44 SD) [t(45) = 2.91, $p < 0.01$, d = 0.87] (Fig. 2 D). This latter finding suggests that CVI participants were slower in their initial visual orientation response (i.e. pre-attentive processing) compared to controls.

To verify the validity of the derived intercept value calculation, we also examined reaction times resulting directly from the zero distractors condition. Again, we found that this value was significantly higher in the CVI group compared to controls (compare CVI: 1004.28 ms ± 169.08 SD, and controls: 834.30 ms ± 99.41 SD) [t(45) = 4.13, $p > 0.001$, d = 1.25]. A regression analysis associating the calculated intercept and recorded reaction time at the zero- distractor condition from both groups revealed that these two measures were significantly correlated [$r^2 = 0.518$, $p < 0.001$].

Regarding ancillary outcomes, we also found that mean gaze error was significantly higher in CVI (6.43 arc degrees ± 2.36 SD) compared to controls (3.22 arc degrees ± 1.00 SD) [t(45) = 5.93, $p < 0.001$, d = 1.81) (Fig. 2 E). This finding suggests that eye gaze patterns to the target were less accurate in CVI participants. Furthermore, mean visual search area in the CVI group (45.31 screen % ± 20.14 SD) was significantly greater compared to controls (20.90 screen % ± 7.90 SD) [t(45) = 5.34, $p < 0.001$, d = 1.64] (Fig. 2 F). The greater value in visual search area observed in CVI participants is suggestive of less precise eye movements to the target compared to controls.

As a second level of analysis, we also investigated possible differences between the two study groups with respect to varying the number of distractors in relation to reaction time (i.e., reaction time × set size function) as well as success rate, gaze error, and visual search area (Fig. 3). A two-way ANOVA for reaction time (with group and set size as factors) showed that at each set size, controls had a significantly lower mean reaction time compared to the CVI group [F(1) = 98.844, $p < 0.001$, $\eta p^2 = 0.235$] (Fig. 3 A). Set size had a significant main effect on mean reaction time [F(6) = 7.305, $p < 0.001$, $\eta p^2 = 0.120$] (Fig. 3 A). There was no interaction effect between group and set size with respect to reaction time [F(6) = 0.155, p = 0.988, $\eta p^2 = 0.003$], with mean reaction time increasing with increasing set size in both groups. A two-way ANOVA for success rate with group and set size as factors showed that at each set size, controls had a significantly higher success rate compared to CVI participants [F(1) = 143.311, $p < 0.001$, $\eta p^2 = 0.235$] (Fig. 3 B). Set size did not have a significant effect on the subjects' success rate [F(6) = 1.567, p = 0.156, $\eta p^2 = 0.028$]. There was no interaction effect between group and set size with respect to set size success rate [F(6) = 0.785, p = 0.582, $\eta p^2 = 0.014$], as success rate did not vary significantly with increasing set size. A two-way ANOVA for gaze error with group and set size as factors showed that at each set size, the control group had a significantly lower mean gaze error compared to CVI [F(1) = 265.692, $p < 0.001$, $\eta p^2 = 0.452$] (Fig. 3 C). Set size had a significant effect on the subjects' gaze error [F(6) = 4.134, $p < 0.001$, $\eta p^2 = 0.072$] (Fig. 3 C). There was no interaction effect between group and set size with respect to gaze error [F(6) = 0.238, p = 0.964, $\eta p^2 = 0.004$], as mean gaze error increased with increasing set size in both groups. A two-way ANOVA for visual search area with group and set size as factors showed that at each set size, the control group had a significantly lower mean visual search area compared to CVI [F(1) = 194.415, $p < 0.001$, $\eta p^2 = 0.\ 0.376$] (Fig. 3 D). Set size had a significant effect on the visual search area for both the control and CVI groups [F(6) = 5.360, $p < 0.001$, $\eta p^2 = 0.091$] (Fig. 3 D). There was no interaction effect between group and set size with respect to visual search area [F(6) = 0.898, p = 0.496, $\eta p^2 = 0.016$], with mean visual search area increasing with increased set size in both groups.

### 3.3. *Experiment 2 – effect of varying spacing and field of view*

To test the effect of varying the spacing between the target and distractors, we compared visual search outcomes of interest between CVI and control participants. A MANOVA with success rate, reaction time, slope, intercept, gaze error, visual search area, and off-screen percentage as factors showed and overall group effect [F(7) = 33.73, $p < 0.001$, $\eta p^2 = 0.69$] and an overall condition effect [F(14) = 5.01, $p < 0.001$, $\eta p^2 = 0.25$]. There was no significant overall interaction effect between group and spacing [F(14) = 1.37, p = 0.17, $\eta p^2 = 0.08$]. A two-way ANOVA with success rate, reaction time, slope, intercept, gaze error, visual search area, and off-screen percentage as factors revealed that there was a significant effect of group on all outcomes of interest (success rate: [F(1) = 117.99, $p < 0.001$, $\eta p^2 = 0.51$], reaction time: [F(1) = 172.08, $p < 0.001$, $\eta p^2 = 0.60$], slope: [F(1) = 53.75, $p < 0.001$, $\eta p^2 = 0.32$], intercept: [F(1) = 99.76, $p < 0.001$, $\eta p^2 = 0.47$], gaze error: [F(1) = 177.97, $p < 0.001$, $\eta p^2 = 0.61$], visual search area: [F(1) = 114.69, $p < 0.01$, $\eta p^2 = 0.50$]). For all outcomes (except slope), spacing had no effect for the CVI nor the control groups, and there was no interaction effect between group and spacing condition. For slope however, there was an effect of condition [F(2) = 6.67, $p < 0.01$, $\eta p^2 = 0.11$] and an interaction effect between group and spacing condition [F(2) = 5.03, $p < 0.01$, $\eta p^2 = 0.08$]. A series of t-tests confirmed that the CVI group showed impaired performance compared to controls on all outcomes of interest [success rate (all $p < 0.001$), reaction time (all $p < 0.001$), intercept (all $p < 0.01$), gaze error (all $p < 0.001$), visual search area (all $p < 0.001$); for full results, see Table 1], except for slope. T-tests revealed that there was a significant group difference with respect to slope for the small [t (26) = − 3.29, $p < 0.05$, d = − 1.72] and large [t(29) = − 2.35, $p < 0.05$, d = − 1.02] spacing conditions. Slope values from the CVI group (small: 23.62 ± 13.85 SD, large: 20.10 ± 16.80 SD) were significantly greater than controls (small: 6.22 ± 3.59 SD, large: 7.32 ± 5.57 SD) at these two spacing conditions. For the medium spacing condition however, there was no statistically significant difference between CVI (10.34 ± 6.61 SD) and control (6.06 ± 4.27 SD) [t(26) = − 1.82, p = 0.10, d = − 0.77] participants (Fig. 4 A).

To test the effect of varying FOV, we compared three different sizes (small, medium, and large) on all visual search outcomes of interest. A MANOVA with success rate, reaction time, slope, intercept, gaze error, visual search area, and off-screen percentage as factors showed and overall group effect $[F(7) = 19.75, p < 0.001, \eta p^2 = 0.66]$, an overall condition effect $[F(14) = 3.45, p < 0.001, \eta p^2 = 0.25]$, and an interaction effect $[F(14) = 2.12, p < 0.05, \eta p^2 = 0.17]$. A two-way ANOVA with success rate, reaction time, slope, intercept, gaze error, visual search area, and off-screen percentage as factors revealed that there was a statistically significant effect of group on all outcomes of interest (success rate: $[F(1) = 115.55, p < 0.001, \eta p^2 = 0.60]$, reaction time: $[F(1) = 106.46, p < 0.001, \eta p^2 = 0.58]$, slope: $[F(1) = 15.76, p < 0.001, \eta p^2 = 0.17]$, intercept: $[F(1) = 70.64, p < 0.001, \eta p^2 = 0.48]$, gaze error: $[F(1) = 101.87, p < 0.001, \eta p^2 = 0.57]$, visual search area: $[F(1) = 78.62, p < 0.001, \eta p^2 = 0.51]$. For all outcomes (except gaze error and visual search area), varying the size of FOV had no significant effect and there was no interaction effect between group and FOV conditions. For gaze error however, there was a significant effect of FOV condition $[F(2) = 11.72, p < 0.001, \eta p^2 = 0.23]$ as well as an interaction effect between group and FOV condition $[F(2) = 3.77, p < 0.05, \eta p^2 = 0.09]$. Similarly, there was a significant effect of condition for visual search area $[F(2) = 15.71, p < 0.001, \eta p^2 = 0.29]$ and a significant interaction effect between group and FOV condition $[F(2) = 3.49, p < 0.05, \eta p^2 = 0.08]$ (Fig. 4 B). Consistent with the aforementioned ANOVA, a series of t-tests revealed that the CVI group showed impaired performance compared to controls on all outcomes at each FOV condition [success rate (all $p < 0.001$), reaction time (all $p < 0.001$), intercept (all $p < 0.01$), gaze error (all $p < 0.001$), visual search area (all $p < 0.01$); for full results, see Table 2].

### *3.4. MANCOVA for factors of interest on visual search performance*

A MANCOVA was conducted using Wilks' Lambda multivariate test to investigate potential associations between verbal IQ, age, and group on the primary visual search outcomes of success rate, reaction time, slope, and intercept. We found that group (i.e., CVI and controls) had a significant collective effect on success rate, reaction time, slope, and intercept $[F(4) = 4.360, p < 0.01, \eta p^2 = 0.353]$ after controlling for verbal IQ and age.

## 4. Discussion

The results observed from this study are consistent with clinical accounts of impaired visual search abilities in individuals with CVI, particularly in relation to finding a target of interest in a cluttered and crowded visual scene (Jacobson et al., 1996; Lam et al., 2010; McDowell & Dutton, 2019). Specifically, we found that CVI participants showed an overall impairment in performance on all of our visual search outcomes of interest when compared to chronologically age-matched controls. Impairments with visual search were also observed in CVI participants with visual acuities at normal/near normal levels, and intact visual field function within the area corresponding to visual testing. Importantly, both CVI and control participants maintained high and comparable levels of task compliance as indexed by calculated mean off-screen percentage values. Taken together, this suggests that observed group differences in our study are likely related to changes associated with early onset neurological injury, rather than potential behavioral confounds such as impaired visual function (i.e. decreased visual acuity or visual field deficit) or simply poor task participation. Our finding of higher order visual processing deficits in CVI participants having normal visual acuity is in line with a number of reports and further points to the importance of developmental damage and the maldevelopment of key central visual processing areas of the brain. Kooiker and colleagues demonstrated impairments with visual search as well as fixation and ocular motor pursuit (Kooiker et al., 2014) in children with CVI compared to controls with neurotypical development. A recent study by Chandna and colleagues (2021) tested steady-state visual evoked potentials (SSVEPs) in response to visual motion in children with CVI and good binocular visual acuity. Compared to age-matched controls, CVI subjects showed significant deficits in the processing of complex (but not elementary) motion patterns (Chandna et al., 2021). In line with the results of Chandna et al. (2021), another study by our group showed that CVI participants had a

**Table 1**
Effect of spacing.

| | Success rate (± SD) | Reaction time (± SD) | Slope (± SD) | Intercept (± SD) | Gaze error (± SD) | Area (± SD) |
|---|---|---|---|---|---|---|
| **Small** | | | | | | |
| Control Mean | 0.89 ± 0.09 | 1044.49 ± 98.00 | 6.22 ± 3.59 | 981.76 ± 119.30 | 2.68 ± 0.74 | 13.51 ± 4.65 |
| CVI Mean | 0.60 ± 0.19 | 1604.36 ± 325.14 | 23.64 ± 13.85 | 1350.81 ± 328.24 | 5.46 ± 1.74 | 33.64 ± 17.59 |
| T statistic | 5.51 | -6.31 | -3.29 | -4.08 | -5.86 | -4.81 |
| p value | < 0.001 | < 0.001 | < 0.05 | < 0.01 | < 0.001 | < 0.01 |
| Effect size | 1.95 | -2.33 | -1.72 | -1.49 | -2.08 | -1.56 |
| **Medium** | | | | | | |
| Control Mean | 0.94 ± 0.04 | 1039.63 ± 109.10 | 6.06 ± 4.27 | 981.23 ± 92.62 | 2.41 ± 0.48 | 13.22 ± 3.94 |
| CVI Mean | 0.62 ± 0.23 | 1531.78 ± 318.91 | 10.34 ± 6.61 | 1413.71 ± 338.79 | 5.16 ± 1.57 | 34.42 ± 15.65 |
| T statistic | 5.24 | -5.62 | -1.82 | -4.69 | -6.41 | -4.99 |
| p value | < 0.001 | < 0.001 | 0.1 | < 0.001 | < 0.001 | < 0.001 |
| Effect size | 1.94 | -2.06 | -0.77 | -1.74 | -2.37 | -1.86 |
| **Large** | | | | | | |
| Control Mean | 0.90 ± 0.11 | 1058.93 ± 106.70 | 7.32 ± 5.57 | 1010.12 ± 101.45 | 2.00 ± 0.47 | 13.66 ± 4.67 |
| CVI Mean | 0.58 ± 0.26 | 1605.28 ± 329.76 | 20.10 ± 16.80 | 1401.72 ± 301.03 | 4.99 ± 1.88 | 35.75 ± 16.86 |
| T statistic | 4.47 | -6.05 | -2.35 | -4.74 | -5.86 | -4.81 |
| p value | < 0.001 | < 0.001 | < 0.05 | < 0.001 | < 0.001 | < 0.001 |
| Effect size | 1.60 | -2.23 | -1.02 | -1.74 | -2.18 | -1.79 |

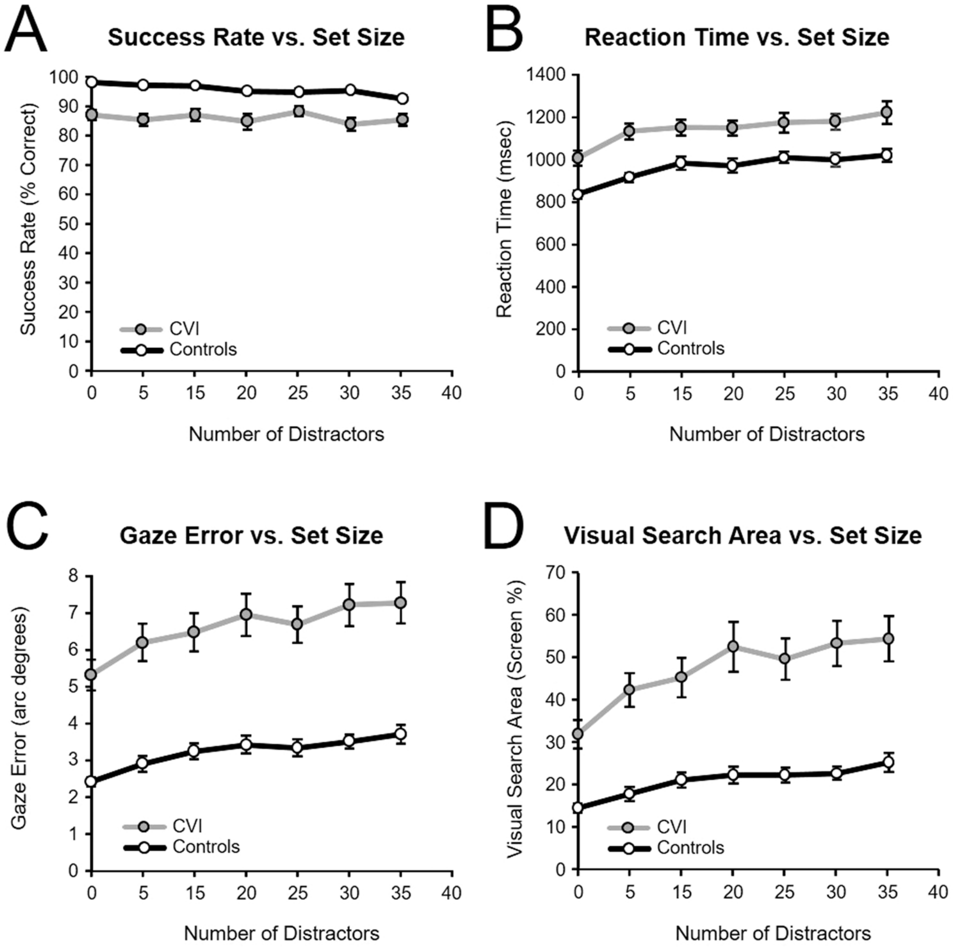

**Fig. 4.** Effect of varying item spacing and FOV. A) Visual search performance was less efficient (indexed by a higher slope value) in CVI compared to controls at the smallest and largest spacing sizes tested. B) Increasing FOV size was associated with a profile of decreased gaze accuracy and precision (as indexed by increased gaze error and visual search area values, respectively). Levels of statistical significance: *p < 0.05, **p < 0.01; ***p < 0.001. Error bars represent ± SEM.

**Table 2**
Effect of field of view.

| | Success rate (± SD) | Reaction time (± SD) | Slope (± SD) | Intercept (± SD) | Gaze error (± SD) | Area (± SD) |
|---|---|---|---|---|---|---|
| **Small** | | | | | | |
| Control Mean | 0.93 ± 0.04 | 1048.32 ± 152.36 | 5.40 ± 3.93 | 1010.87 ± 158.19 | 1.55 ± 0.41 | 4.24 ± 1.75 |
| CVI Mean | 0.48 ± 0.28 | 1564.84 ± 304.25 | 11.29 ± 8.22 | 1423.97 ± 406.44 | 4.44 ± 1.85 | 22.19 ± 13.03 |
| T statistic | 6.5 | -6.35 | -1.7 | -3.9 | -6.18 | -5.48 |
| p value | < 0.001 | < 0.001 | 0.143 | < 0.01 | < 0.001 | < 0.01 |
| Effect size | 2.25 | -2.15 | -1.46 | -1.34 | -2.16 | -1.93 |
| **Medium** | | | | | | |
| Control Mean | 0.92 ± 0.08 | 1082.87 ± 136.82 | 5.77 ± 2.80 | 1023.52 ± 139.60 | 1.86 ± 0.47 | 7.65 ± 2.57 |
| CVI Mean | 0.46 ± 0.28 | 1594.80 ± 221.95 | 14.36 ± 7.72 | 1514.77 ± 519.23 | 5.09 ± 2.08 | 30.31 ± 15.53 |
| T statistic | 6.51 | -8.36 | -2.67 | -3.71 | -6.13 | -5.79 |
| p value | < 0.001 | < 0.001 | 0.04 | < 0.01 | < 0.001 | < 0.001 |
| Effect size | 2.23 | -2.78 | -1.48 | -1.29 | -2.14 | -2.04 |
| **Large** | | | | | | |
| Control Mean | 0.89 ± 0.10 | 1104.76 ± 145.15 | 8.66 ± 6.01 | 1025.87 ± 136.91 | 2.30 ± 0.63 | 12.19 ± 3.62 |
| CVI Mean | 0.45 ± 0.29 | 1671.45 ± 313.80 | 11.06 ± 8.07 | 1632.52 ± 470.46 | 6.06 ± 2.33 | 40.06 ± 19.95 |
| T statistic | 5.85 | -6.82 | -0.77 | -5.04 | -6.3 | -5.54 |
| p value | < 0.001 | < 0.001 | 0.46 | < 0.001 | < 0.001 | < 0.001 |
| Effect size | 2.03 | -2.32 | -0.34 | -1.75 | -2.20 | -1.94 |

significantly higher mean motion coherence threshold (in response to optic flow motion) compared to controls despite having visual acuities within normal range (Pamir et al., 2021).

Analyzing visual search outcomes as a function of varying set size (i.e., number of surrounding distractors) revealed a general response profile consistent with worsening performance with increasing visual task difficulty and demands. Furthermore, manipulating the spacing between items and FOV also had a greater effect on search performance in CVI compared to control participants. We found that visual search in CVI was less efficient at the smallest as well as largest spacing conditions tested, with highest search efficiency occurring at the medium spacing condition. In contrast, increasing FOV size was associated with a profile of decreasing gaze accuracy and precision in CVI compared to control participants. Finally, a multivariate analysis of covariance (MANCOVA) confirmed that there was a significant collective effect between the CVI and control groups with respect to visual search performance after controlling for verbal IQ and age.

The slope of the reaction time × set size function characterizes the rate of attentional shifting between items as well as the ability to filter out irrelevant items (Sternberg, 1966). Shallow slope values (i.e., approaching 0 msec/item) are indicative of "efficient" search performance while steeper slope values (in the range of 20–60 msec/item) are considered "inefficient" (Joseph et al., 2009; Wolfe, 2016; Wolfe et al., 2011). The observation of comparatively worse visual search efficiency in CVI (i.e. steeper slope value) is interpreted to suggest that this group had greater difficulty in shifting attention and ignoring distracting stimuli in the visual scene. We also found that the intercept value derived from the reaction time × set size function was higher in the CVI group compared to controls. The higher intercept value suggests that in addition to decreased visual search efficiency, there is also a contribution of non-search related mechanisms related to initial visual orienting responses. Specifically, individuals with CVI appear to have a delay in initial pre-search processing abilities. This may be related to difficulties with discriminating targets from distractors, directing attention to the target, and a slowed ocular motor response (saccade) to the target once it was detected.

Considering the behavioral outcomes collected from Experiment 1, it was evident that there was variability in terms of their respective effect sizes. The range of observed effect sizes was 0.87–1.82 which can be considered as relatively "small" based on Cohen's criteria. The outcomes having the largest effect sizes were success rate ($d = 1.79$) and gaze error ($d = 1.81$) suggesting that these two metrics may have the greatest discriminative value between CVI and control participants with respect to visual search performance on this task.

In our second experiment, we found that visual search efficiency was lowest (i.e. highest slope value) in CVI compared to controls at the smallest and largest spacing conditions tested (though comparable at the medium spacing condition). This suggests that for CVI participants, there may be an optimal spacing distance between elements supporting visual search performance. We also observed that increasing FOV in CVI was associated with a gaze profile of decreased gaze accuracy and precision (as indexed by increased gaze error and visual search area, respectively). These findings appear consistent with previous reports describing how individuals with CVI experience increased difficulty with finding objects in crowded and cluttered visual scenes (Lam et al., 2010; McDowell & Dutton, 2019) and perceive only a very small area of space at a time (Philip & Dutton, 2014).

The neurophysiological basis underlying these observations remains unknown but is likely related to a delayed and/or maldevelopment of top-down attentional control processes (see (Gil-Gomez de Liano et al., 2020) for further discussion). It is important to recall that visual search is multifaceted and draws from interrelated sensory, perceptual, and cognitive processes. This includes visuospatial aspects related to the encoding of visual properties that distinguish relevant from irrelevant information, as well as executive functions such as the deployment of selective attention to a target and ignoring distractors (Scerif et al., 2004). In the setting of early neurological injury (as in the case of CVI), we can expect that the sequence and coordination of developmental processes supporting visual search would be altered. The general profile of impaired performance speaks to the notion that early onset injury in CVI impacts numerous aspects of visual search including pre-attentive perceptual processing and attention. However, other clinical observations such gaze apraxia, simultanagnosia, visual agnosia, and impaired visual guidance of movement (optic ataxia) (McDowell, 2020; Williams et al., 2011) may also be contributory and further highlight the complex clinical profile of this condition.

To our knowledge, the first characterization of visual search performance in CVI was carried out by Zihl and Dutton (2015) using a simple feature search paradigm (locating a diamond shaped target presented among circles on a uniform white background; set size varied from 1 to 17 items). Computing reaction time × set size functions, the investigators found that visual search in control subjects ($n = 5$, aged between 8 and 10 years) showed a profile that was highly efficient (i.e. a slope value approaching 0) and consistent with a "parallel" mode of search. In contrast, performance collected from two CVI participants (aged 8 and 11 years old, CVI associated with PVL) showed an increase in reaction time with increasing set size, consistent with less efficient (i.e. steeper slope) and "serial" mode of search (Zihl & Dutton, 2015). While only a small study sample was tested, these preliminary findings represent an early objective characterization of visual search behavior in CVI.

Impairments with pre-attentive processing appear to be in line with other eye tracking studies describing early visual processing deficits in CVI including evidence of impaired saccadic inhibitory control and maintaining sustained attention (Maioli et al., 2019), as well as delays in visual orienting responses (Kooiker et al., 2014, 2015; Pel et al., 2011). Kooiker and colleagues used eye tracking with participants diagnosed with (and at risk for) CVI to measure reaction times in response to a cartoon image presented at different locations on a screen. This group found that orienting responses were delayed in CVI compared to typically developing children. Interestingly, children with CVI also took longer to respond to simple visual and auditory detection tasks which is suggestive of a more general sensorimotor deficit (Kooiker et al., 2014, 2015). A recent study by Ben Itzhak et al. (2021) showed that impaired visual orienting in CVI was correlated with indices obtained from visuo-perceptual assessments related to daily visual behaviors (Ben Itzhak et al., 2021). This further supports accumulating evidence of impaired visuospatial processing abilities in this population.

The multiple observations drawn from this study can be reconciled by considering a framework in which individuals with CVI have difficulties with deploying, distributing, and shifting visual selective attention within the visual field (proposed by Zuidhoek, 2020, but see also (Fink et al., 1996) and (Petersen & Posner, 2012) for similar accounts related to visual attention). Specifically, processing information within a complex visual scene requires the contribution and interplay of two key functions. First, global visual selective attention which allows an individual to “zoom out” and gain an image overview. Second, local visual selective attention for a “zoom in” to discriminate fine details and elements within a visual scene (note that impairments in both these functions can be present in the same individual, and are not mutually exclusive). An impairment in global visual selective attention means that an individual has to move their eyes constantly and take more time to get a general impression of a visual scene. This often leads to fatigue and feeling overwhelmed, especially with high task demands. There may also be difficulties perceiving complex visuospatial figures and comprehending the interrelationship between elements of a complex visual scene. In this case, making the size of the visual scene smaller, or partially occluding the visual periphery may help with gaining an overview. In contrast, an impairment with local visual selective attention can lead to difficulty focusing on details, especially with seeing separate elements in crowded visual situations. Therefore, it may be difficult to identify and locate an object of interest as details are perceived as indistinct. In this case, reducing viewing distance (i.e. increasing magnification of the object of interest) may allow for easier recognition of details. Furthermore, strategies that increase target saliency and reducing background clutter may be helpful (e.g. emphasizing unique target features to facilitate identification such as color, motion, luminance, as well as size and shape (Wolfe & Horowitz, 2004) see also Donnelly et al., 2007). Our observation of impaired visual search performance in CVI in response to 1) increasing distractor number, 2) with small and large spacings between search elements, and 3) decreased accuracy and precision with increased FOV size, all appear consistent with the notion of impaired global and local visual selective attention processing. Consider a situation where an individual with CVI must interact with items on a desktop or workspace. Our characterization of visual search performance and factors that modulate search abilities suggests that objects of interest are more likely to be found when given sufficient time and when they are perceived as salient (i.e. easily discriminated from surrounding items). Furthermore, presenting items in isolation or with optimal spacing between them, with appropriate magnification, and within a FOV size that is not too large may also help mitigate challenges associated with impaired visual search as well as visuospatial and visual selective attention processing.

The characterization of visual search abilities in CVI in naturalistic tasks and scenes remains limited. McDowell (2020) developed a novel and easily deployable tool called the Austin Playing Card Assessment to help identify visual perceptual difficulties in CVI. The task requires a participant to search and pick up pairs of standard playing cards of varying array sizes. Task difficulty is progressively increased by the number of cards explored in the search array (from 1 pair amongst 4 cards to 5 pairs amongst 12 cards). Similar to the general behavioral profile presented here, McDowell showed that participants with CVI were slower than controls in performing the task, with longer times being taken with increasing task difficulty (McDowell, 2020). Finally, Chang and Borchert (2021) have used eye tracking to assess ocular motor behavior in younger children with CVI and with multiple developmental impairments. Using a passive viewing experimental protocol (i.e. not requiring specific task instructions), free viewing behavior of naturalistic visual stimuli such as still images and movies was assessed. Consistent with our findings, preliminary results from this group suggests that children with CVI showed longer latency initiating saccades while viewing and searching for a subject of interest in a naturalistic scene. Furthermore, fixations on the object of interest improved (i.e. resembled patterns observed in controls) when motion cues and plain (compared to a visually complex) background were used (Chang & Borchert, 2021). This latter observation further speaks to the sensitivity of CVI subjects to complex visual scenes, and supports the notion that adaptations such as increasing target saliency and decreasing background clutter may be helpful in improving search and overall functional vision performance in this population (Little & Dutton, 2014; McDowell & Budd, 2018).

The general strengths of the study are in relation to the nature of the task design and multiple measures collected allowing for a more comprehensive characterization of visual search performance in CVI. This highlights the value of developing novel assessment approaches to help uncover higher order visual perceptual deficits which could be potentially overlooked, particularly in cases where visual acuity function is within normal range (van Genderen et al., 2012). The use of a VR based task allows for sufficient experimental control so that the effect of manipulating various features of a visual scene and task can be investigated (Bennett et al., 2019; Parsons, 2015). Further, data collection using eye-tracking allows for the objective measurement of performance without the requirement of manual or verbal responses on the part of the participant. This is particularly relevant in the case of CVI, as many individuals may have associated neurodevelopmental comorbidities (such as cerebral palsy, seizure disorder, motor impairments, and cognitive issues) that can confound the interpretation of recorded behavioral responses. The relatively high and comparable task compliance observed in both CVI and control participants allow for more direct comparisons to be made with respect to visual search performance.

Finally, possible study limitations should be considered. Most notable is the fact that in order to participate in this study, CVI participants were required to have a level of visual acuity and ocular motor function imposed by the eye tracker calibration parameters required for accurate data capture. This issue is a source of selection bias that can limit the overall generalizability of our results across the heterogeneous clinical profile of CVI. In future studies, we plan to adapt our VR paradigms for a broader range of visual functioning levels, as well investigate other feature dimensions such as modifying background clutter and target object saliency. Furthermore, despite comparable levels of task compliance, there may be group differences in visual search performance related to underlying developmental factors (even after controlling for age and verbal IQ as was done in this study). Future studies should consider comparing performance in CVI with control participants matched for developmental age, as well as associating visual search abilities with daily visual behaviors (Ben Itzhak et al., 2021).

## CRediT authorship contribution statement

All authors contributed to this study and manuscript.

## Funding Statement

This work was supported by grants from the NIH/NEI (R21 EY030587 and R01 EY03097).

## What this Paper Adds

Cerebral visual impairment (CVI) is often associated with complex visuospatial perceptual deficits. For example, individuals with CVI report difficulties locating a target of interest in a cluttered and crowded visual scene. These higher order visual perceptual deficits are typically not assessed as part of a standard ophthalmological examination. Furthermore, it remains unknown how manipulating task demands and other environmental factors influence visual search performance in this population. In this study, we developed a novel and naturalistic virtual reality (VR) based environment combined with eye tracking to objectively assess visual search performance. The behavioral relevance of the task design and high participant engagement allowed for direct comparisons to be made between CVI participants and age-matched controls. Our results demonstrate that participants with CVI show an overall impairment with respect to visual search performance. This response profile was consistent with less efficient search as well as slower initial (i.e., pre-search) visual orienting responses (as indexed by increased slope and intercept values derived from reaction time × set size functions). Furthermore, search efficiency was more negatively affected at the smallest as well as largest spacing conditions tested, while increasing visual search area (field of view) was associated with a profile of decreased gaze accuracy and precision. This novel VR based approach may have important clinical applications in helping to assess environmental factors that affect functional visual processing in CVI.

## Data Availability

Data will be made available on request.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ridd.2022.104364.

## References

Ben Itzhak, N., Kooiker, M. J. G., van der Steen, J., Pel, J. J. M., Wagemans, J., & Ortibus, E. (2021). The relation between visual orienting functions, daily visual behaviour and visuoperceptual performance in children with (suspected) cerebral visual impairment. *Research in Developmental Disabilities, 119*, Article 104092. https://doi.org/10.1016/j.ridd.2021.104092

Bennett, C. R., Bailin, E. S., Gottlieb, T. K., Bauer, C. M., Bex, P. J., & Merabet, L. B. (2018). Virtual reality based assessment of static object visual search in ocular compared to cerebral visual impairment. *HCI, 8*, 28–38.

Bennett, C. R., Bex, P. J., Bauer, C. M., & Merabet, L. B. (2019). The assessment of visual function and functional vision. *Seminars in Pediatric Neurology, 31*, 30–40. https://doi.org/10.1016/j.spen.2019.05.006

Bennett, C. R., Bex, P. J., & Merabet, L. B. (2021). Assessing visual search performance using a novel dynamic naturalistic scene. *Journal of Vision, 21*(1), 5. https://doi.org/10.1167/jov.21.1.5

Boot, F. H., Pel, J. J., van der Steen, J., & Evenhuis, H. M. (2010). Cerebral visual impairment: Which perceptive visual dysfunctions can be expected in children with brain damage? A systematic review. *Research in Developmental Disabilities, 31*(6), 1149–1159. https://doi.org/10.1016/j.ridd.2010.08.001

Chandna, A., Nichiporuk, N., Nicholas, S., Kumar, R., & Norcia, A. M. (2021). Motion processing deficits in children with cerebral visual impairment and good visual acuity. *Investigative Ophthalmology & Visual Science, 62*(14), 12. https://doi.org/10.1167/iovs.62.14.12

Chang, M. Y., & Borchert, M. S. (2021). Methods of visual assessment in children with cortical visual impairment. *Current Opinion in Neurology, 34*(1), 89–96. https://doi.org/10.1097/WCO.0000000000000877

Colenbrander, A. (2005). Visual functions and functional vision. *International Congress Series, 1282*, 482–486.

Donnelly, N., Cave, K., Greenway, R., Hadwin, J. A., Stevenson, J., & Sonuga-Barke, E. (2007). Visual search in children and adults: Top-down and bottom-up mechanisms. *Quarterly Journal of Experimental Psychology, 60*(1), 120–136. https://doi.org/10.1080/17470210600625362

Dutton, G. N. (2013). The spectrum of cerebral visual impairment as a sequel to premature birth: an overview. *Documenta Ophthalmologica, 127*(1), 69–78. https://doi.org/10.1007/s10633-013-9382-1

Dutton, G. N., & Lueck, A. H. (2015). Impairment of vision due to damage to the brain. In A. H. L. A. G. N. Dutton (Ed.), *Vision and the brain: Understanding cerebral visual impairment in children* (pp. 3–20). AFB Press New York.

Dutton, G. N., McKillop, E. C., & Saidkasimova, S. (2006). Visual problems as a result of brain damage in children. *British Journal of Ophthalmology, 90*(8), 932–933. https://doi.org/10.1136/bjo.2006.095349

Dutton, G. N., Saaed, A., Fahad, B., Fraser, R., McDaid, G., McDade, J., Mackintosh, A., Rane, T., & Spowart, K. (2004). Association of binocular lower visual field impairment, impaired simultaneous perception, disordered visually guided motion and inaccurate saccades in children with cerebral visual dysfunction-a retrospective observational study. *Eye, 18*(1), 27–34. https://doi.org/10.1038/sj.eye.6700541

Eckstein, M. P. (2011). Visual search: A retrospective. *Journal of Vision, 11*(5). https://doi.org/10.1167/11.5.14

Fazzi, E., Signorini, S. G., Bova, S. M., La Piana, R., Ondei, P., Bertone, C., Misefari, W., & Bianchi, P. E. (2007). Spectrum of visual disorders in children with cerebral visual impairment. *Journal of Child Neurology, 22*(3), 294–301. https://doi.org/10.1177/08830738070220030801

Fink, G. R., Halligan, P. W., Marshall, J. C., Frith, C. D., Frackowiak, R. S., & Dolan, R. J. (1996). Where in the brain does visual attention select the forest and the trees? *Nature, 382*(6592), 626–628. https://doi.org/10.1038/382626a0

Gil-Gomez de Liano, B., Quiros-Godoy, M., Perez-Hernandez, E., & Wolfe, J. M. (2020). Efficiency and accuracy of visual search develop at different rates from early childhood through early adulthood. *Psychonomic Bulletin & Review, 27*(3), 504–511. https://doi.org/10.3758/s13423-020-01712-z

Hoyt, C. S. (2003). Visual function in the brain-damaged child [review]. *Eye, 17*(3), 369–384. https://doi.org/10.1038/sj.eye.6700364

Jacobson, L., Ek, U., Fernell, E., Flodmark, O., & Broberger, U. (1996). Visual impairment in preterm children with periventricular leukomalacia–visual, cognitive and neuropaediatric characteristics related to cerebral imaging. *Developmental Medicine and Child Neurology, 38*(8), 724–735. https://doi.org/10.1111/j.1469-8749.1996.tb12142.x

Johnson, B. P., Lum, J. A., Rinehart, N. J., & Fielding, J. (2016). Ocular motor disturbances in autism spectrum disorders: Systematic review and comprehensive meta-analysis. *Neuroscience & Biobehavioral Reviews, 69*, 260–279. https://doi.org/10.1016/j.neubiorev.2016.08.007

Joseph, R. M., Keehn, B., Connolly, C., Wolfe, J. M., & Horowitz, T. S. (2009). Why is visual search superior in autism spectrum disorder? *Developmental Science, 12*(6), 1083–1096. https://doi.org/10.1111/j.1467-7687.2009.00855.x

Kooiker, M. J., Pel, J. J., & van der Steen, J. (2014). Viewing behavior and related clinical characteristics in a population of children with visual impairments in the Netherlands. *Research in Developmental Disabilities, 35*(6), 1393–1401. https://doi.org/10.1016/j.ridd.2014.03.038

Kooiker, M. J., Pel, J. J., & van der Steen, J. (2015). The relationship between visual orienting responses and clinical characteristics in children attending special education for the visually impaired. *Journal of Child Neurology, 30*(6), 690–697. https://doi.org/10.1177/0883073814539556

Kran, B., & Mayer, D. L. (2011). Visual impairment and brain damage. In M. B. Taub, M. Bartuccio, & D. Maino (Eds.), *Visual diagnosis and care of the patient with special needs* (p. 135). Lippincott, Williams & Wilkins.

Kran, B. S., Lawrence, L., Mayer, D. L., & Heidary, G. (2019). Cerebral/cortical visual impairment: A need to reassess current definitions of visual impairment and blindness. *Seminars in Pediatric Neurology, 31*, 25–29. https://doi.org/10.1016/j.spen.2019.05.005

Lam, F. C., Lovett, F., & Dutton, G. N. (2010). Cerebral visual impairment in children: A longitudinal case study of functional outcomes beyond the visual acuities. *Journal of Visual Impairment & Blindness, 104*(10), 625–635.

Little, S., & Dutton, G. N. (2014). Some children with multiple disabilities and cerebral visual impairment can engage when enclosed by a 'tent': Is this due to Balint syndrome? *British Journal of Visual Impairment, 33*(1), 66–73.

Maioli, C., Falciati, L., Galli, J., Micheletti, S., Turetti, L., Balconi, M., & Fazzi, E. M. (2019). Visuospatial attention and saccadic inhibitory control in children with cerebral palsy. *Frontiers in Human Neuroscience, 13*, 392. https://doi.org/10.3389/fnhum.2019.00392

McConnell, E. L., Saunders, K. J., & Little, J. A. (2021). What assessments are currently used to investigate and diagnose cerebral visual impairment (CVI) in children? A systematic review. *Ophthalmic & Physiological Optics, 41*(2), 224–244. https://doi.org/10.1111/opo.12776

McCulloch, D. L., Mackie, R. T., Dutton, G. N., Bradnam, M. S., Day, R. E., McDaid, G. J., Phillips, S., Napier, A., Herbert, A. M., Saunders, K. J., & Shepherd, A. J. (2007). A visual skills inventory for children with neurological impairments [Research Support, Non-U.S. Gov't]. *Developmental Medicine and Child Neurology, 49*(10), 757–763. https://doi.org/10.1111/j.1469-8749.2007.00757.x

McDowell, N. (2020). A pilot study of the Austin Playing Card Assessment: A tool to detect and find the degree of visual perceptual difficulties related to clutter. *British Journal of Visual Impairment, 38*(2), 118–136.

McDowell, N., & Budd, J. (2018). The perspectives of teachers and paraeducators on the relationship between classroom clutter and learning experiences for students with cerebral visual impairment. *Journal of Visual Impairment & Blindness, 112*(3), 248–260.

McDowell, N., & Dutton, G. N. (2019). Hemianopia and features of balint syndrome following occipital lobe hemorrhage: Identification and patient understanding have aided functional improvement years after onset. *Case Reports in Ophthalmological Medicine, 2019*, Article 3864572. https://doi.org/10.1155/2019/3864572

McKillop, E., & Dutton, G. N. (2008). Impairment of vision in children due to damage to the brain: A practical approach. *British and Irish Orthoptic Journal, 5*, 8–14.

Merabet, L. B., Mayer, D. L., Bauer, C. M., Wright, D., & Kran, B. S. (2017). Disentangling how the brain is "wired" in cortical (cerebral) visual impairment. *Seminars in Pediatric Neurology, 24*(2), 83–91. https://doi.org/10.1016/j.spen.2017.04.005

Ortibus, E., Laenen, A., Verhoeven, J., De Cock, P., Casteels, I., Schoolmeesters, B., Buyck, A., & Lagae, L. (2011). Screening for cerebral visual impairment: value of a CVI questionnaire. *Neuropediatrics, 42*(4), 138–147. https://doi.org/10.1055/s-0031-1285908

Pamir, Z., Bauer, C. M., Bailin, E. S., Bex, P. J., Somers, D. C., & Merabet, L. B. (2021). Neural correlates associated with impaired global motion perception in cerebral visual impairment (CVI). *NeuroImage: Clinical, 32*, Article 102821. https://doi.org/10.1016/j.nicl.2021.102821

Parsons, T. D. (2015). Virtual reality for enhanced ecological validity and experimental control in the clinical, affective and social neurosciences. *Frontiers in Human Neuroscience, 9*, 660. https://doi.org/10.3389/fnhum.2015.00660

Pel, J., Does, L. V., Boot, F., Faber, T. D., Steen-Kant, S. V., Willemsen, S., & Steen, H. V. (2011). Effects of visual processing and congenital nystagmus on visually guided ocular motor behaviour. *Developmental Medicine and Child Neurology, 53*(4), 344–349. https://doi.org/10.1111/j.1469-8749.2010.03857.x

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience, 35*, 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Philip, S. S., & Dutton, G. N. (2014). Identifying and characterising cerebral visual impairment in children: A review. *Clinical and Experimental Optometry, 97*(3), 196–208. https://doi.org/10.1111/cxo.12155

Sakki, H. E. A., Dale, N. J., Sargent, J., Perez-Roche, T., & Bowman, R. (2018). Is there consensus in defining childhood cerebral visual impairment? A systematic review of terminology and definitions. *British Journal of Ophthalmology, 102*(4), 424–432. https://doi.org/10.1136/bjophthalmol-2017-310694

Scerif, G., Cornish, K., Wilding, J., Driver, J., & Karmiloff-Smith, A. (2004). Visual search in typically developing toddlers and toddlers with Fragile X or Williams syndrome. *Developmental Science, 7*(1), 116–130. https://doi.org/10.1111/j.1467-7687.2004.00327.x

Sternberg, S. (1966). High-speed scanning in human memory. *Science, 153*(3736), 652–654. https://doi.org/10.1126/science.153.3736.652

Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12*(1), 97–136. https://doi.org/10.1016/0010-0285(80)90005-5

van Genderen, M., Dekker, M., Pilon, F., & Bals, I. (2012). Diagnosing cerebral visual impairment in children with good visual acuity. *Strabismus, 20*(2), 78–83. https://doi.org/10.3109/09273972.2012.680232

Volpe, J. J. (2009). Brain injury in premature infants: A complex amalgam of destructive and developmental disturbances [review]. *Lancet Neurology, 8*(1), 110–124. https://doi.org/10.1016/S1474-4422(08)70294-1

Williams, C., Northstone, K., Sabates, R., Feinstein, L., Emond, A., & Dutton, G. N. (2011). Visual perceptual difficulties and under-achievement at school in a large community-based sample of children. *PLoS One, 6*(3), Article e14772. https://doi.org/10.1371/journal.pone.0014772

Wolfe, J. M. (2016). Visual search revived: The slopes are not that slippery: A reply to Kristjansson (2015). *Iperception, 7*(3), Article 2041669516643244. https://doi.org/10.1177/2041669516643244

Wolfe, J. M. (2020). Visual search: How do we find what we are looking for? *Annual Review of Vision Science, 6*, 539–562. https://doi.org/10.1146/annurev-vision-091718-015048

Wolfe, J. M., Alvarez, G. A., Rosenholtz, R., Kuzmova, Y. I., & Sherman, A. M. (2011). Visual search for arbitrary objects in real scenes. *Attention, Perception, & Psychophysics, 73*(6), 1650–1671. https://doi.org/10.3758/s13414-011-0153-3

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience, 5*(6), 495–501. https://doi.org/10.1038/nrn1411

Wolfe, J. M., Oliva, A., Horowitz, T. S., Butcher, S. J., & Bompas, A. (2002). Segmentation of objects from backgrounds in visual search tasks. *Vision Research, 42*(28), 2985–3004. https://doi.org/10.1016/s0042-6989(02)00388-7

Zihl, J., & Dutton, G. H. (2015). Visual disorders. In G. N. D. J. Zihl (Ed.), *Cerebral visual impairment in children: Visuoperceptive and visuocogntive disorders* (pp. 61–115). Springer-Verlag Wien.

Zuidhoek, S. (2020). *CVI in the picture: When the brain is the cause of visual impairment in children*. Huizen. Visio.