The table-top visual search ability test for children and young people: normative response time data from typically developing children.

Jonathan Waddington[1], Jade Pickering[2, 3], and Timothy Hodgson[3].

[1]WESC Foundation, [2]University of Manchester, and [3]University of Lincoln.

Abstract

Five real-world tasks were developed to test the visual search ability of children and young people, and detect potential deficits in visual search ability. Each task involved searching for a set of target objects among distracting objects on a table-top. Performance on the Table-top Visual Search Ability Test for Children (TVSAT-C) was measured as the time spent searching for targets divided by the number of targets found. 108 typically developing children (3-11 years old) and 8 children with vision impairment (7-12 years old) participated in the study. A significant correlation was found between log-transformed age and log-transformed performance ($R^2 = 0.65, p = 4 \times 10^{-26}$) in our normative sample, indicating a monomial power law relationship between age and performance with an exponent of -1.67, 95% CI $[-1.90, -1.43]$. We calculated age-dependent percentiles and used the 5th percentile as a cut-off for detecting a visual search deficit, giving a specificity of 92.6%, 95% CI $[86.1\%, 96.2\%]$ and sensitivity of 87.5%, 95% CI $[52.9\%, 97.8\%]$ for the test. Further studies are required to calculate measures of reliability and external validity. We have made the protocol and age-dependent normative data available for those interested in using the test in research or practice, and to illustrate the smooth developmental trajectory of visual search ability during childhood.

Introduction

Search is a fundamental human skill involved in performing a wide range of daily tasks and achieving operational goals, such as finding a favourite book on a bookshelf lined with other books. Searching for an object defined by one or more perceptual features (e.g. colour, size, or shape) requires attentional processes to actively scan the environment for the features that define the target object relative to distracting objects. Computerised visual search tasks have been used to study this ability in healthy adults and children but many aspects of the development of visual attention in children remain poorly understood (Johnson, 2019). Studies that have examined visual search ability across the lifespan have revealed an inverted U-shaped performance pattern with performance increasing from childhood into adulthood and declining from middle age (Plude, Enns, and Brodeur, 1994). Increased efficiency in processes that integrate the perceptual features of objects and orient the focus of attention between locations and objects are thought to drive improvements in search ability between childhood and adulthood; whereas decreased efficiency in attentional orienting alone is thought to be the cause of decline in later life (Trick and Enns, 1998).

The visual search ability of children with visual impairments depends on the presence or absence of oculomotor impairments, visual field impairments and attentional impairments such as an increased influence of multiple distracting objects in close proximity or “crowding” (Huurneman, Cox, Vlaskamp, and Boonstra, 2014). Adults with partial visual field loss (i.e. hemianopia) present with inefficient search strategies as indexed by eye movement recordings, whilst others develop compensatory search strategies that enable them to perform visual search almost as effectively as adults without field loss (Zihl, 1995). The factors that determine development of compensatory search strategies remain unclear, and cannot be explained simply as a matter of time since or extent of the visual field deficit (Zihl, 1999, 2000). However, the observation that compensatory search strategies can be developed spontaneously has led to the development of visual search training and rehabilitation programmes designed to promote compensatory search strategies in practice (e.g. Turton et al., 2015).

Previous research into visual search training has focused on improving visual search skills in adults with either hemianopia or spatial inattention caused by stroke. Most modern training tools designed for this purpose are based on actively searching for digital targets displayed on a screen (e.g. Aimola et al., 2014; Ong et al., 2015; Sahraie, Smania, and Zihl, 2016; Chesham et al., 2019). Currently studies are also focusing on developing training protocols to improve visual search skills in children with visual field impairments arising from perinatal and acquired brain injury (Waddington and Hodgson, 2017; Ivanov et al., 2018; Waddington et al., 2018), or as a consequence of surgical interventions to treat other conditions such as hemi-disconnection surgery to treat intractable epilepsy (Koenraads et al. 2014). When assessing the outcomes of vision rehabilitation it is essential to evaluate whether learned skills transfer to real world activities. As such, there is a need for assessment tools that can give objective outcome measures that don't involve actively searching for digital targets displayed on a screen. The development of such tools may prove useful in the future to assess the visual abilities of children and individualise support plans or interventions in an educational or (re)habilitation context. Assessments focussed purely on testing visual acuity and visual fields are unable to capture deficits in visual attention and higher order visual processing functions that are apparent in children with cerebral vision impairments (CVIs) (Kran et al. 2019) so suitable protocols that assess visual attentional functions may also be of use in this respect (Vancleef, Janssens, Petré, Wagemans, and Ortibus, 2019).

We have developed a battery of five table-top tasks to measure visual search ability in children. The Table-top Visual Search Ability Test for Children, or the TVSAT-C, has already been used to evaluate changes in the visual search ability of children and young people with homonymous visual field loss before and after visual search training (Waddington et al., 2018). The aim of the present study was to investigate how age affected visual search performance on the TVSAT-C with a normative sample of children. A secondary aim was to investigate whether these reference values could be used to detect deficits in visual search ability with a pilot sample of eight visually impaired children with a range of medical conditions.

Methods

Participants

This study received ethical approval from the University of Lincoln's School of Psychology Research Ethics Committee. We identified candidates for participation during a public engagement event held at the University of Lincoln. Children from 3 to 11 years old and their parents were invited to attend the five day event for one morning or afternoon, to take part in a variety of research studies designed to be engaging for children and young people. In this particular study we included any child that expressed an interest in participating and excluded the data for children who self-reported a vision impairment or other special educational need. 214 candidates attended the event and 122 participants assented with parental consent. We excluded the data from 14 participants who reported special educational needs and analysed the data from 108 participants (55 female; median age = 6.4 years, interquartile range = 5.1 – 7.7 years, absolute range = 3.1 – 10.5 years).

Comparative data were also obtained from 8 participants with vision impairment (7-12 years old). These participants were identified during two separate studies to develop and evaluate a therapeutic game, designed to promote visual search training for young people with homonymous visual field loss (Waddington, Linehan, Gerling, Hicks, and Hodgson, 2015; Waddington et al., 2018). Those studies received ethical approval from the University of Lincoln's School of Psychology Research Ethics Committee and the United Kingdom National Research Ethics Service Committee North East – Newcastle & North Tyneside 1. Five participants were diagnosed with visual field impairment due to brain injury, two were diagnosed with albinism, and one was diagnosed with congenital fibrosis of the extraocular muscles.

Tasks, Materials and Protocol

The TVSAT-C tasks were adapted from a test previously used to evaluate outcome measures after visual search training in adults with hemianopia (Pambakian, Mannan, Hodgson, and Kennard, 2004). The changes were designed to make the tasks more age-appropriate and to reduce reliance on confounding factors such as manual dexterity and intelligence. For example, we adapted one task that involved threading beads bearing letters of the alphabet onto a leather lace in alphabetical order to a task that involved correctly matching brightly coloured magnets in the shape of letters of the alphabet to a series of letters written on a card. We also selected test materials that were reasonably large, bold and plain-coloured, as well as easy to pick up and manipulate.

The materials required to perform the TVSAT-C included one Attribute Blocks Desk Set (Learning Resources; Illinois, USA; LER 1270; https://www.learningresources.co.uk/attribute-blocks-desk-set) that originally contained 60 plastic blocks: a combination of five shapes, two sizes, two thicknesses, and three colours. The hexagon shapes and small sized blocks were excluded, leaving 24 attribute blocks in the test kit. The test kit also required one set of Wooden Letter Alphabet Magnets (Melissa & Doug; Connecticut, USA; MAD1111255E1; https://www.melissaanddoug.com/wooden-letter-alphabet-magnets/448.html) that originally contained 52 upper- and lowercase magnetic letters in blue, green, red and yellow. Only the uppercase letters were included in the test kit. We also used a modular Compact Disc (CD) Storage Rack with the capacity to hold 120 CDs (Westpoint Design; Castle Douglas, UK; CD120; https://cdanddvdstorage.com/products), eight standard jewel CD cases, and card in four pastel shades (blue, green, red, and yellow). The coloured card was fixed to the clear plastic exterior of the CD cases to create four pairs of coloured CD cases. The rest of the test kit included 24 UK denomination coins (eight 1p, eight 2p, and eight 5p), one plain black tablecloth, A3 sized (21.0 × 29.7cm) white card, and a black bullet tip marker. Time to complete the tasks was measured using a stopwatch on a smartphone with the assessor manually starting and stopping the stopwatch.

Each task involved searching for one set of target objects among sets of distracting objects on a table covered with a black tablecloth. Task 1 included 3 sets of 8 coloured blocks (blue, red, and yellow) and task 2 included 4 sets of 6 geometric blocks (circles, rectangles, squares, and triangles). Both task 1 and task 2 included the same attribute blocks so there was the same combination of colours and shapes in both tasks (i.e. two blue circles, two blue rectangles, … two yellow squares, two yellow triangles). Task 3 included 3 sets of 8 UK denomination coins (1p, 2p, and 5p). Task 4 included 5 pseudorandomly selected target letters from the modern English alphabet, with the remaining 21 letters acting as distracting objects. Task 5 included 4 sets of 2 coloured compact disk cases (blue, green, red, and yellow). We selected task order and target sets pseudorandomly before each assessment using a simple random number generator (see Table 1 for example).

Table 1. Representative test protocol for the TVSAT-C after randomisation of task order and targets

Task order	All sets (number of objects in each set)	Target set
1. Coins	1p (8), 2p (8), 5p (8)	5p
2. Letters	Uppercase letters (26)	C T V W I

3. Blocks (colour)	Blue (8), red (8), yellow (8)	Blue
4. Blocks (shape)	Squares (6), triangles (6), circles (6), rectangles (6)	Squares
5. CDs	Blue (2), green (2), red (2), yellow (2)	Red

We prepared tasks 1-4 by selecting a corresponding diagram of the required targets illustrated on white A3 card. The table-top was covered in a black tablecloth. The white A3 card was placed in front of the participant by the assessor with the diagram face down. The sets of target and distracting objects were then placed at random around the perimeter of the white card. At the start of each task the card was turned over to reveal the diagram of the target objects, the assessor then gave a verbal prompt (e.g. “Can you find all the blue objects?” or “Can you find the letters: C, T, V, W, and I?”) to begin the task (see Figure 1 for examples). We prepared task 5 by placing a CD rack (80cm in length) in front of the participant and four CDs, each separated by two compartments on the storage rack, at either end of the rack. The assessor gave a verbal prompt (e.g. “Can you find the red CDs?”) to begin the task. Participants indicated they had found a target by picking it up and placing it in front of them. Each task ended when the participant had placed the last target in front of them or when they indicated that they couldn’t find any more of the targets. The time taken to complete each task and the number of targets found were recorded.

[Insert figure 1]

Figure 1. Representative photographs of tasks from the TVSAT-C

Photographs of five representative table-top search tasks from the TVSAT-C, including: (a) 24 UK denomination coins with an equal mix of three values (1p, 2p, and 5p), (b) 26 letters of the alphabet, (c) 24 attribute blocks with an equal mix of three colours (blue, red, and yellow), (d) 24 attribute blocks with an equal mix of four shapes (squares, circles, rectangles, and triangles), and (e) 8 coloured compact disk cases with an equal mix of four colours (blue, green, red, and yellow) presented on a display rack. Note that target objects for the search tasks (a), (b), (c), and (d) are displayed on an A3 sized (21.0 × 29.7cm) white card at the start of the task and represent the tasks displayed in the protocol from Table 1.

Analysis

We defined the response time performance on the visual search tasks as the total time taken to complete each task divided by the total number of targets found. We evaluated a simple linear regression model including log-transformed visual response times and log-transformed age. We assessed the residuals of the regression for departure from normality with the Anderson-Darling test. Subsequently, we defined a 5th percentile function that depended on age as the cut-off for typically developing visual search skills. We calculated the specificity and sensitivity of the test using the results from our normative and comparative group participants respectively. Confidence intervals for specificity and sensitivity were produced with the Wilson score method (Newcombe, 1998).

Results

We plotted participants' visual response times on the TVSAT-C against their age (Figure 2a), which indicated a nonlinear relationship. The results of Spearman's rank correlation indicated a significant decreasing monotonic dependency between age and visual response times ($r_S(106) = -0.816$, $p = 6.05 \times 10^{-27}$). We calculated a simple linear regression to predict log-transformed visual response times based on log-transformed age. A significant regression equation was found ($F(1{,}106) = 200$, $p = 4 \times 10^{-26}$) with an adjusted R^2 of 0.650, indicating a monomial power law relationship between age and visual response times. After inverting logs we found that participants' mean visual response times were equal to $\exp(4.21) \cdot (age)^{-1.67}$ seconds when age was measured in years. In plain English, participants' visual response times decreased 16.7% for each 10.0% increase in age on average. We calculated the confidence interval for the exponent to determine whether the relationship could be approximated by a simple reciprocal relationship and found the exponent to be -1.67, 95% CI $[-1.90, -1.43]$, indicating it could not.

[Insert figure 2]

Figure 2. Age-related performance on the TVSAT-C.

Plots of performance on the TVSAT-C against age, demonstrating: (a) raw data from a normative sample of 108 children, (b) population percentiles estimated from the normative sample (bold solid line = 50th percentile, thin solid lines = 25th and 75th percentiles, dash lines = 10th and 90th percentiles, dot-dash lines = 5th and 95th percentiles, dot lines = 1st and 99th percentiles) and (c) raw data from a sample of vision impaired children (empty circles = diagnosed visual field impairment due to brain injury, diamonds = diagnosed albinism, cross = diagnosed congenital fibrosis of the extraocular muscles).

We compared the studentised residuals of the linear regression with the predicted values of visual response times and found a symmetrical random distribution, indicating that the assumptions of linearity, additivity, and homoscedasticity had not been violated. An Anderson-Darling test for normality on the standardised residuals found no significant difference between the distribution of standardised residuals and the Gaussian distribution ($A^2 = 0.398, p = 0.365$).

We therefore modelled visual response time quantile trajectories as:

$$rt_q = \exp\left(4.21 - \sigma\Phi^{-1}(q)\right) \cdot (age)^{-1.67}$$

where $\Phi^{-1}(\cdot)$ is the standard probit function, σ is the age-controlled population standard deviation of log-transformed visual response times, and q is the desired quantile. We estimated $\sigma = 0.358$ log units from the error variance calculated during the simple linear regression. We plotted the trajectories of the 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles for reference (Figure 2b). We set the cut-off point for detecting a visual search deficit at the 5th percentile and calculated the specificity of the tests based on our normative data to be 92.6%, 95% CI $[86.1\%, 96.2\%]$. For clarity, the function describing the cut-off point is:

$$rt = 33.4(age)^{-1.67}$$

We plotted the visual response time results of eight young participants with vision impairment (see Methods for diagnoses) who had completed the TVSAT-C against their age, and the trajectories of the 5th, 50th, and 95th percentiles for reference (Figure 2c). The data demonstrated that all eight visually impaired participants had visual response times that were lower than the average for their age, and seven of the eight participants had visual response times that were lower than the 5th percentile. We calculated the sensitivity of the TVSAT-C to be 87.5%, 95% CI $[52.9\%, 97.8\%]$. These results indicated that the TVSAT-C may have good sensitivity for detecting impairment of visual search ability but we require more data from persons with vision impairment to be more confident.

We calculated the quantile performance of the eight visually impaired participants using the model:

$$q = \Phi\left(\frac{\ln\left(\frac{vrt}{age^{-1.67}}\right) - 4.21}{-0.358}\right)$$

where $\Phi(\cdot)$ is the standard Normal cumulative density function. The percentile performance ranks of the eight visually impaired participants were: 23.8, 0.1, <0.1, 3.0, 0.2, <0.1, <0.1, and <0.1 in order of age. We also conducted an independent-samples t-test to compare the percentile performance ranks for the non-visually impaired male and female participants. There was no significant difference in percentile performance ranks between boys ($M = 49.5$, $SD = 30.8$) and girls ($M = 48.6$, $SD = 27.7$); ($t(106) = 0.171$, $p = 0.865$) on the TVSAT-C.

Discussion

We have developed the TVSAT-C, a real-world test of visual search ability for children that does not require computerised assessment. A normative sample of test results from 108 children between the ages of 3 and 11 demonstrated a smooth developmental trajectory of visual search performance that improved with age following a monomial power law function with an exponent of -1.67. We were able to calculate quantiles and define a cut-off score (the 5th percentile) for typical visual search ability. Using a small sample of visually impaired children with a range of medical conditions, this cut-off gave the TVSAT-C a specificity of 92.6% and sensitivity of 87.5% for discriminating between children with and without vision impairment, indicating it could be a useful tool for detecting visual search deficits in children with vision impairments such as CVI.

Previous studies have shown that mean response times across a range of tasks decrease throughout childhood and adolescence and it has been suggested that age differences reflect rapid improvement in a general processing speed during childhood, with slower improvement during adolescence (Kail, 1991). Psychometric measures of processing speed based on the number of visual tasks completed within a fixed period of time increase as a sublinear function during childhood and adolescence (Kail and Ferrer, 2007). Eye movement response times such as saccadic latency for visually guided, memory guided, and antisaccade tasks also decrease from late childhood to adulthood, following a reciprocal function (Luna, Garver, Urban, Lazar, and Sweeney, 2004). The reciprocal of response time is response rate, which we might expect to be directly correlated with processing speed when neurological signals are travelling similar distances through the same neural networks. Our results follow a similar pattern, although we found response time decreased by 16.7% for every 10% increase in age, i.e. the age-related decrease in response time on the current task occurred over smaller differences in age than would be predicted from a reciprocal relationship.

Whether this developmental change in visual search ability with age can be explained by changes in specific attentional functions (e.g. perceptual feature integration, attention shifting or distractor inhibition) or instead reflects global changes in processing speed is not possible to infer from the current study. Future studies could use eye tracking during search tasks in children to address this question. Rates of fixation on non-target distractor items of the same colour as the target might be greater in younger children (reflecting problems in suppressing the influence of distractor items), as might be the duration of each fixation period between saccadic eye movements (potentially indicating problems in shifting attention). Another possibility is that search becomes more systematic or strategic with age. Studies in healthy adults (Gilchrist and Harvey, 2000; Hollingworth and Luck, 2009; Klein and MacInnes, 1999) and patients with neurological injuries leading to hemi-spatial neglect (Husain et al., 2001) have highlighted the importance of memory (for previously searched items and location), inhibition of return (whereby shifts in attention towards recently inspected items are inhibited), and use of an ordered strategy (e.g. searching top to bottom and left to right) in guiding complex search. Interestingly, these are functions usually associated with the prefrontal and parietal cortex of the brain rather than traditional visual areas in the occipital cerebral cortex. Impairments in these processes, whilst unlikely to be revealed by traditional tests that assess visual acuity or visual field integrity, would nevertheless have a detrimental impact on completing tasks that require searching for objects from children with acquired brain injury or developmental disorders.

Another interpretation of the observed continuous relationship between search times and age is that it represents underlying processes of neural development that in turn influence cognitive processing and performance. Early results of longitudinal MRI studies of brain development demonstrated that grey matter volume followed an inverted U-shaped growth pattern peaking in early adolescence, whilst white matter volume followed a sublinear growth pattern through childhood and adolescence with decline beginning in middle age (Giedd et al., 1999; Bartzokis et al., 2001; Lenroot and Giedd, 2006). More recent studies have indicated that grey matter volume may begin to decrease during early childhood after an initial growth spurt during infancy, and white matter volume may have plateaued by mid-to-late adolescence (Mills et al., 2016). Diffusion tensor imaging studies have demonstrated tract-specific age-related changes in white matter microstructure (e.g. myelination) that appear to contribute to improvements in processing speed and thus a range of cognitive abilities during childhood that generally peak in young adulthood (Peters et al., 2014; Chevalier et al., 2015). Oculomotor control circuits may be particularly important in determining visual search performance and cortical influences on mid-brain oculomotor circuitry continue to develop through infancy, childhood and adolescence (Johnson, Posner, and Rothbart, 1991; Luna, Velanova, and Geier, 2008). Neurobiologically therefore, development appears to be a continuous process, which contrasts with influential Piaget frameworks that emphasise discrete and discontinuous developmental stages (Klahr, 2012). The developmental trajectory of real-world visual search performance in typically developing children described here appears to mirror the continuous process of white matter structural changes inferred from neuroimaging studies, and can be seen as supporting the former rather than the latter perspective.

The TVSAT-C was designed to assess visual search performance in a realistic setting that does not rely on a computerised display. We believe this gives the TVSAT-C greater ecological validity than standard computerised tests. For example the field of view over which objects were displayed and had to be searched for in the table-top tasks (we estimate

60 degrees of visual arc) was much wider than that typically occupied by a computerised display (typically 30 degrees at standard viewing distance). Potential disadvantages of using table-top tests with real objects rather than a digital display is that more time is required to prepare and conduct the TVSAT-C and there is less accuracy as well as potential bias in recording response times. Also, the presence of comorbid motor disorders such as cerebral palsy could make it difficult to interact with physical test materials, reducing performance on the TVSAT-C. We have used objects of a size and shape that are relatively simple to pick up and manipulate in an attempt to counter this. However, the presence of neurological and physical conditions that impair reaching and grasping would need to be taken into account in interpretation of impaired performance in the test.

Both the reliability and validity of the TVSAT-C still require further evaluation. Inter-tester reliability is likely to be good. While there might be some variability in how quickly testers respond on the stopwatch this will be small in comparison to the total time spent searching for the target objects. Test-retest reliability is a potential source for concern. Response times to visual targets are known to be variable from one task to the next. A single response is not a reliable measure, and this is why we included many target objects to search for across the tasks. The external validity of the TVSAT-C could be evaluated simply by comparing results from this test with the results of a standard computerised visual search test from the same participants.

The TVSAT-C is a real-world objective measure of visual search ability. The materials required to perform the test are easy and relatively inexpensive to obtain, and the test is simple to run. We would recommend the TVSAT-C as an assessment tool in combination with further investigations. When a vision impairment that could affect visual search ability has been diagnosed or is suspected, the TVSAT-C could be used to infer whether a child has spontaneously learned to compensate for their vision impairment or whether they may require training to improve their visual search ability. We have recently reported on a study in which we used performance on the TVSAT-C to measure improvements in the visual search performance of children and young people with partial visual field loss after they participated in gamified visual search training (Waddington et al., 2018), demonstrating its usefulness as a research tool. Further work to assess the reliability and validity of the test as well as eye tracking investigations of visual search strategies in children will help further develop the TVSAT-C as a potentially useful assessment battery for children with a range of visual impairments, including CVIs.

Acknowledgements

We would like to thank the Summer Scientist Week team for organising the community event at the University of Lincoln where we recruited participants, and Sarah Flynn for her assistance with data collection. We would also like to thank the participating children and families. This work was supported by funding from the WESC Foundation, the Technology Strategy Board (now Innovate UK) and the Medical Research Council of the United Kingdom, as part of a Knowledge Transfer Partnership (Ref: KTP008989). The authors report no conflicts of interest.

References

Aimola, L., Lane, A., Smith, D., Kerkhoff, G., Ford, G., and Schenk, T. (2014). Efficacy and feasibility of home-based training for individuals with homonymous visual field defects. *Neurorehabilitation and neural repair*, *28*(3), 207-218.

Bartzokis, G., Beckson, M., Lu, P., Nuechterlein, K., Edwards, N., and Mintz, J. (2001). Age-related changes in frontal and temporal lobe volumes in men: a magnetic resonance imaging study. *Archives of General Psychiatry*, *58*(5), 461-465.

Chesham, A., Gerber, S., Schütz, N., Saner, H., Gutbrod, K., Müri, R., Nef, T., and Urwyler, P. (2019). Search and match task: development of a taskified match-3 puzzle game to assess and practice visual search. *JMIR Serious Games*, *7*(2), e13620. doi: 10.2196/13620.

Chevalier, N., Kurth, S., Doucette, M., Wiseheart, M., Deoni, S., Dean, D., O'Muircheartaigh, J., Blackwell, K., Munakata, Y., and LeBourgeois, M. (2015). Myelination is associated with processing speed in early childhood: preliminary insights. *PLoS One*, *10*(10), e0139897. doi: 10.1371/journal.pone.0139897.

Giedd, J., Blumenthal, J., Jeffries, N., Castellanos, F., Liu, H., Zijdenbos, A., Paus, T., Evans, A., and Rapoport, J. (1999). Brain development during childhood and adolescence: a longitudinal MRI study. *Nature Neuroscience*, *2*, 861-863.

Gilchrist, I., and Harvey, M. (2000). Refixation frequency and memory mechanisms in visual search. *Current Biology*, *10*(19), 1209–1212.

Hollingworth, A., and Luck, S. (2009). The role of visual working memory (VWM) in the control of gaze during visual search. *Attention, Perception & Psychophysics*, *71*(4), 936–949.

Husain, M., Mannan, S., Hodgson, T., Wojcuilik, E., Driver, J. and Kennard, C. (2001). Impaired spatial working memory across saccades contributes to abnormal search in parietal neglect. *Brain*, *124*(5), 941–952.

Huurneman, B., Cox, R., Vlaskamp, B., and Boonstra, F. (2014). Crowded visual search in children with normal vision and children with visual impairment. *Vision Research, 96,* 65-74.

Ivanov, I., Kuester, S., MacKeben, M., Krumm, A., Haaga, M., Staudt, M., Cordey, A., Gehrlich, C., Martus, P., and Trauzettel-Klosinski, S. (2018). Effects of visual search training in children with hemianopia. *PLoS One*, *13*(7), e0197285. doi: 10.1371/journal.pone.0197285.

Johnson, M., Posner, M., and Rothbart, M. (1991). Components of visual orienting in early infancy: contingency learning, anticipatory looking, and disengaging. *Journal of Cognitive Neuroscience*, *3*(4), 335-344.

Johnson, S. (2019) Development of visual-spatial attention. In *Current Topics in Behavioral Neurosciences*. Berlin, Heidelberg: Springer. doi: 10.1007/7854_2019_96.

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin*, *109*(3), *490-501*.

Kail, R., and Ferrer, E. (2007). Processing speed in childhood and adolescence: longitudinal models for examining developmental change. *Child Development*, *78*(6), 1760-1770.

Klahr, D. (2012). Beyond Piaget: a perspective from studies of children's problem solving abilities. In A. Slater and P. Quinn (Eds.), *Developmental Psychology: Revisiting the Classic Studies* (pp. 56-70). London, UK: Sage Publications.

Klein, R.M., and MacInnes, W.J. (1999). Inhibition of return is a foraging facilitator in visual search. *Psychological Science*, *10*(4), 346–352.

Koenraads Y., van der Linden, D., van Schooneveld M., Imhof S., Gosselaar P., Porro G., and Braun, K. (2014). Visual function and compensatory mechanisms for hemianopia after hemispherectomy in children. *Epilepsia*, *55*(6), 909–917.

Kran, B., Lawrence L., Mayer, D., and 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.

Lenroot, R., and Giedd, J. (2006). Brain development in children and adolescents: Insights from anatomical magnetic resonance imaging. *Neuroscience and Biobehavioral Reviews*, *30*, 718-729.

Luna, B., Garver, K., Urban, T., Lazar, N., and Sweeney, J. (2004). Maturation of cognitive processes from late childhood to adulthood. *Child Development*, *75*(5), 1357-1372.

Luna, B., Velanova, K., and Geier, C. (2008). Development of eye-movement control. *Brain and Cognition*, *68*(3), 293-308.

Mills, K., Goddings, A-L., Herting, M., Meuwese, R., Blakemore, S-J., Crone, E., Dahl, R., Güroğlu, B., Raznahan, A., Sowell, E., and Tamnes, C. (2016). Structural brain development between childhood and adulthood: convergence across four longitudinal samples. *NeuroImage*, *141*, 273-281.

Newcombe, R. (1998). Interval estimation for the difference between independent proportions: comparison of eleven methods. *Statistics in Medicine*, *17*(8), 873-890.

Ong, Y., Jacquin-Courtois, S., Gorgoraptis, N., Bays, P., Husain, M., and Leff, A. (2015). Eye-Search: a web-based therapy that improves visual search in hemianopia. *Annals of Clinical and Translational Neurology*, *2*(1), 74-78.

Pambakian, A., Mannan, S., Hodgson, T., and Kennard, C. (2004). Saccadic visual search training: a treatment for patients with homonymous hemianopia. *J Neurol Neurosurg Psychiatry*, *75*(10), 1443-1448.

Peters, B., Ikuta, T., DeRosse, P., John, M., Burdick, K., Gruner, P., Prendergast, D., Szeszko, P., and Malhotra, A. (2014). Age-related differences in white matter tract microstructure are associated with cognitive performance from childhood to adulthood. *Biological Psychiatry*, *75*(3), 248-256.

Plude, D., Enns, J., and Brodeur, D. (1994). The development of selective attention: A lifespan overview. *Acta Psychologica*, *86*(2-3), 227-272.

Sahraie, A., Smania, N., and Zihl, J. (2016). Use of NeuroEyeCoach™ to improve eye movement efficacy in patients with homonymous visual field loss. *BioMed Research International*, *2016*, 5186461. doi: 10.1155/2016/5186461.

Trick, L., and Enns, J. (1998). Lifespan changes in attention: the visual search task. *Cognitive Development*, *13*(3), 369-386.

Turton, A., Angilley, J., Chapman, M., Daniel, A., Longley, V., Clatworthy, P., and Gilchrist, I. (2015). Visual search training in occupational therapy – an example of expert practice in community-based stroke rehabilitation. *British Journal of Occupational Therapy*, *78*(11), 674-687.

Vancleef, K., Janssens, E., Petré, Y., Wagemans, J., and Ortibus, E. (2019). Assessment tool for visual perception deficits in cerebral visual impairment: development and normative data of typically developing children. *Developmental Medicine & Child Neurology*. Advance online publication. doi: 10.1037/a0028240.

Waddington, J., Linehan, C., Gerling, K., Hicks, K., and Hodgson, T. (2015, April). Participatory design of therapeutic video games for young people with neurological vision impairment. In *CHI '15 Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems.* Paper presented at CHI 2015: The ACM CHI Conference on Human Factors in Computing Systems, Seoul Republic of Korea (pp.3533-3542). New York, NY: ACM Press.

Waddington, J., and Hodgson, T. (2017). Review of rehabilitation and habilitation strategies for children and young people with homonymous visual field loss caused by cerebral vision impairment. *British Journal of Visual Impairment*, *35*(3), 197-210.

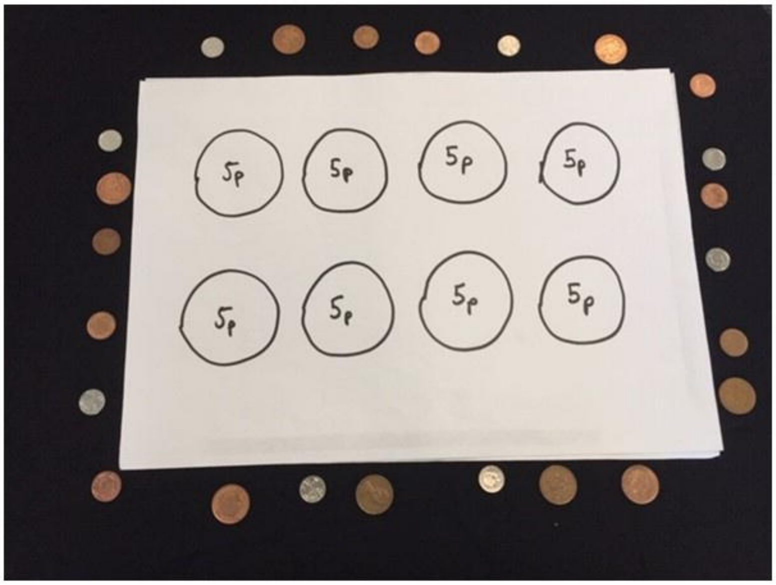
Waddington, J., Linehan, C., Gerling, K., Williams, C., Robson, L., Ellis, R., and Hodgson, T. (2018). Evaluation of Eyelander, a video game designed to engage children and young people with homonymous visual field loss in compensatory training. *Journal of Visual Impairment and Blindness*, *112*(6), 717-730.

Zihl, J. (1995). Visual scanning behavior in patients with homonymous hemianopia. *Neuropsychologia*, *33*, 287-303.

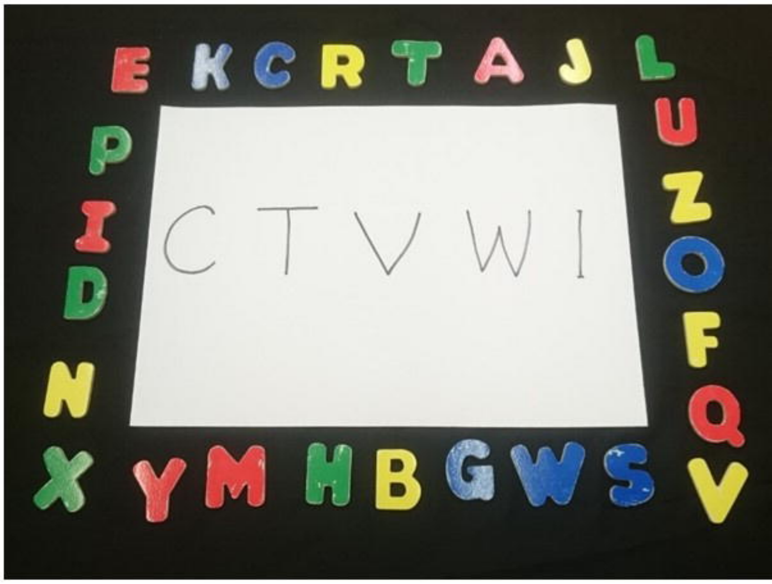
Zihl, J. (1999). Oculomotor scanning performance in subjects with homonymous visual field disorders. *Visual Impairment Research*, *1*, 23-31.

Zihl, J. (2000). *Rehabilitation of visual disorders after brain injury*. Hove, UK: Psychology Press Ltd.

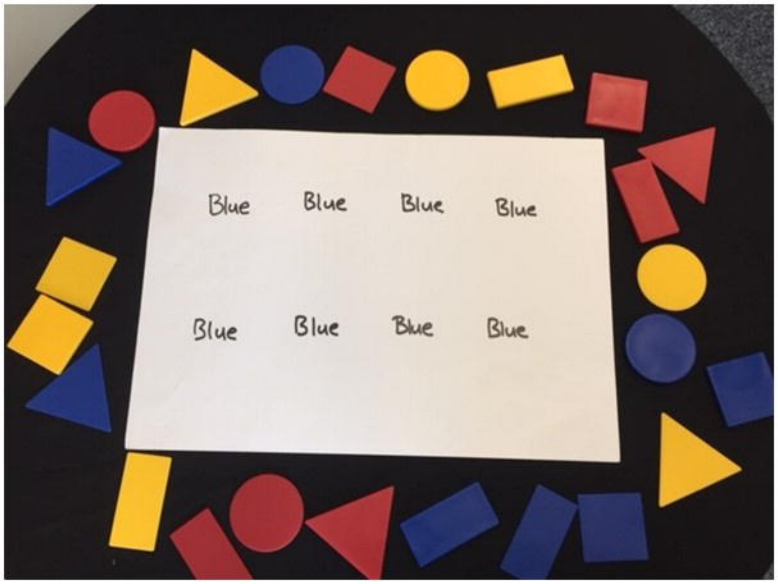
a


5p
5p
5p
5p
5p
5p
5p
5p

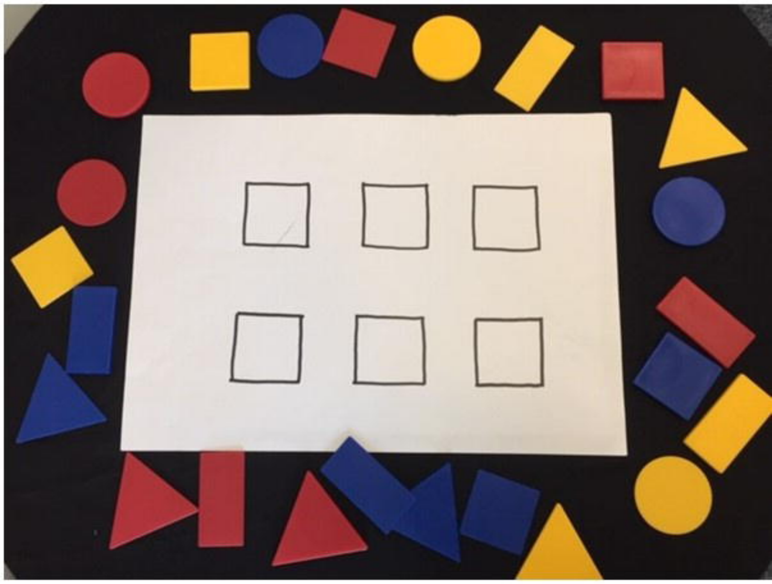
b


E K C R T A J L
P I D N X
Y M H B G W S
U Z O F Q V
C T V W I

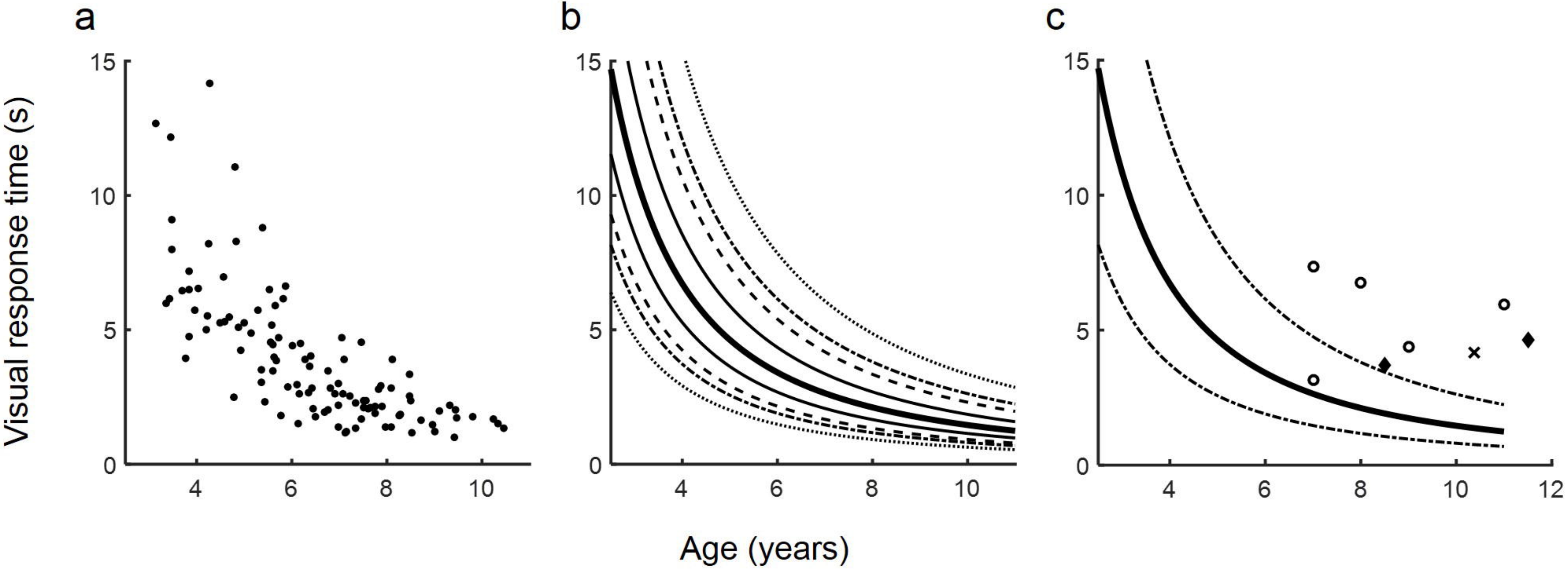
c


Blue Blue Blue Blue
Blue Blue Blue Blue

d



e

a
b
c
Visual response time (s)
Age (years)
0
5
10
15
4
6
8
10
12