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Different trajectories in the development of visual acuity with different levels of crowding: The Milan Eye Chart (MEC)

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ABSTRACT

Eye charts are typically optimized to assess visual acuity (VA) with constant and controlled spacing, while close-to-acuity crowding limits letter identification in the normal fovea when adjacent letters are closely spaced. Here we developed a clinical tool that enables the assessment of acuity with different levels of crowding. In a cross-sectional study, we examined the developmental trajectories with our newly devised Milan Eye Chart (MEC). A total of 252 children of 1st, 3rd and 5th grade were assessed with the MEC using SLOAN letter optotypes with 100%, 50%, 25% and 12.5% inter-optotype spacing. Results show an interaction between spacing and grade. The performance to the 100% standard VA was not significantly different among grades, while the narrow spaced acuity (12.5% spacing) strongly improved with the grade. The different trajectories of acuity measured with high spaced and low spaced eye-charts suggest that the mechanisms able to reduce the crowding effects develops later than VA, and it is, at least in part, dissociated by the psychophysiological development of lower level visual mechanisms. The MEC charts are feasible and useful in assessing visual acuity with different level of crowding during the whole lifespan. The opportunity to assess crowding-limited acuity in early age is particularly relevant since it plays a significant role in amblyopia screening.

1. Introduction

Visual Acuity (VA) is one of the key indicators of the quality of spatial vision (Bailey & Lovie-Kitchin, 2013). It expresses the spatial resolution ability of the visual system and its loss of integrity is one of the two criteria used to define low-vision (Bailey, 2006). According to the International Organization for Standardization (ISO), VA is the: *"number characterizing the ability of the visual system to recognize optotypes"* (ISO, 2017). Different eye charts use various optotypes (symbols) to assess VA such as Sloan letters, Tumbling E, Landolt rings and Lea symbols. According to clinicians and researchers, the best charts use a logarithmic progression of the optotypes size (Bailey & Lovie-Kitchin, 2013; Carkeet & Bailey, 2017; Cole, 2014; Elliott, 2016; Lovie-Kitchin, 2015). A standard "Bailey – Lovie" design of the VA charts is based on five symbols for each line, and the horizontal and vertical inter-optotype spacing is the same symbol size (referred as 100% inter-optotype spacing). Modern eye charts are typically optimized to assess visual acuity (VA) taking into account the effects of inter-letter spacing (generally defined "crowding" in the field of VA) with a constant value across size [e.g., ETDRS charts (Ferris, Kassoff, Bresnick, & Bailey, 1982)].

Crowding is a perceptual phenomenon in which target identification is influenced by the presence of adjacent stimuli (Strasburger, Rentschler, & Jüttner, 2011; Stuart & Burian, 1962). Crowding has been described to limit peripheral vision (Bouma, 1970; Toet & Levi, 1992) as well as foveal identification when targets are small, covering only a few minutes of arc, close to the acuity threshold (Coates & Levi, 2014; Latham & Whitaker, 1996; Siderov, Waugh, & Bedell, 2013). Crowding is a substantial limitation to reading (Pelli et al., 2007). It plays a significant factor in limiting reading speed in the normal periphery (Chung, 2007; Pelli et al., 2007) and during reading acquisition (e.g., Kwon, Legge, & Dubbels, 2007) and later in life with aging (Liu, Patel, & Kwon, 2017). Abnormal crowding has also been shown to be at the root of the letter recognition in the amblyopic eye (Hussain, Webb, Astle, & McGraw, 2012; Levi, 2013; Levi, Song, & Pelli, 2007; Song, Levi, & Pelli, 2014), in developmental dyslexia (e.g. Martelli, Di Filippo,

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Spinelli, & Zoccolotti, 2009) as well as in patients with posterior cortical atrophy that shows impaired reading (Crutch & Warrington, 2007). Critical spacing is the smallest distance between flankers and target that allows correct identification of the target (Jeon, Hamid, Maurer, & Lewis, 2010; Pelli, Palomares, & Majaj, 2004). To measure a VA regardless of crowding, the inter-optotype spacing needs to be higher than critical spacing.

Crowding is a phenomenon and the use of this term did not take automatically into account explanatory mechanisms (Pelli et al., 2007). The effort to measure crowding is made more complicated by the presence of other visuo-spatial interaction effect, such as overlap masking (see Doron, Spierer, & Polat, 2015; Song et al., 2014 for an exhaustive distinction between crowding and overlap masking). To simplify the understanding, in the context of VA measurements and in the clinical literature of amblyopia all these spatial interaction effects are merged and referred with the descriptive term "crowding" (Atkinson, Anker, Evans, Hall, & Pimm-Smith, 1988; Lalor, Formankiewicz, & Waugh, 2016; Sailoganathan, Rou, Buja, & Siderov, 2018; Saul & Taylor, 2015; VIP Study, 2003). We have followed the same approach in the present study and we have used the term "crowding" to describe the manipulation of inter-letter spacing and its effects on letter recognition regardless of specific explanatory mechanisms.

At first, taking into consideration the influence of the different spatial interaction effects on clinical measurement of VA, Flom, Weymouth, and Kahneman (1963) found that 5 bars (1 bar = 1/5 of letter size or the dimension of the Landolt C gap) represented the critical spacing for the discrimination of the orientation of the letter C. Consequently, most VA charts were successively built using this spacing (Bailey & Lovie, 1976; Ferris et al., 1982; Kay, 1983; McGraw & Winn, 1993; Sailoganathan et al., 2018). However, using letters as flankers, more recent studies have shown different VA thresholds when comparing 100% inter-optotype spacing to single target presentation (Doron et al., 2015; Norgett & Siderov, 2011; Semenov, Chernova, & Bondarko, 2000), resulting in lower VA for 100% spaced stimuli. Because the 100% spaced stimuli eye chart is not entirely uncrowded, the Vision in Preschoolers (VIP) Study Group (2003) correctly called these charts "crowded" compared to the totally uncrowded single presentation. VA charts with 100% inter-optotype spacing enable to control crowding in measuring VA, particularly for amblyopia, in which the spatial interaction effects play an important role (Flom, 1991; Song et al., 2014; Stuart & Burian, 1962). VA measurement in children is relevant for detecting amblyopia or refractive errors during screening programs (Jonas et al., 2017). Furthermore, uncrowded VA may be an incomplete indicator of visual functioning in amblyopic individuals who show lower acuity for letters recognition in an array than for an isolated letter, due to spatial interaction effects (Atkinson & Braddick, 1983).

Several studies have measured the developmental changes in acuity- and crowding-limited size thresholds (Atkinson et al., 1988; Bondarko & Semenov, 2005; Doron et al., 2015; Flom et al., 1963; Kothe & Regan, 1990; Norgett & Siderov, 2011; Semenov et al., 2000). For disentangling the effect of crowding, authors typically compare performance across different tests characterized by multiple or single stimuli presentation (Doron et al., 2015; Norgett & Siderov, 2011). However, there is only partial agreement among studies. Some studies report similar developmental trajectories for acuity measured with and without crowding (e.g., Kothe & Regan, 1990), while others show a small or no change in crowding across age (Flom et al., 1963; Manny, Fern, & Loshin, 1987; Norgett & Siderov, 2011). In contrast, Semenov et al. (2000), measured crowded and uncrowded VA in children from 3 to 9 years old. They found that acuity reaches the adult level at 7 years while crowding reaches the adult level at 9 years of age. Differently, Doron et al. (2015) found the adult level for crowding at 6–7 years of age. Norgett and Siderov (2011), compared single and crowded items to test VA in two groups of children (younger: 4–6 years old and older: 7–9 years old), and found more crowding in the younger group. Atkinson et al. (1988), instead, found no difference in crowding between the adults and the 5–7 years old children and suggested that acuity reaches the adult level at the age of 3 while crowding reaches the adult level at the age of 5. Bondarko and Semenov (2005) found that the influence of crowding on VA decreases over a long time course up to 16–17 years of age.

Discrepancies across studies may be related to the target-flanker confusability and the different inter-optotypes spacing used. Many studies have used lines or boxes as flankers instead of confounding symbols. In adults, simple bars placed on the four sides of a target letter, or boxes around letters, influence target recognition to a lesser extent than optotypes similar to the target (Lalor et al., 2016). Lalor et al. (2016) measured VA and crowding in adults with several optotypes (with different flankers) specifically designed for children. They found that similarity between flankers and target has a more significant effect on VA thresholds than boxes surrounding the target. The authors conclude that flankers should be placed closer than available VA charts and should be similar to the target optotype to assess crowding-limited VA. This suggestion has also been proposed in the context of amblyopia screening (Atkinson & Braddick, 1983; Formankiewicz & Waugh, 2013; Song et al., 2014). Many charts with single symbols surrounded by flanking bars or symbols are available in the market [e.g., Glasgow acuity cards (McGraw & Winn, 1993)]. Nevertheless, no agreement between those measures is reported (Sailoganathan et al., 2018), confirming different sensitivity to crowding.

Overall, there is currently no agreement to the best way to test VA in development that enables comparisons across different crowding conditions (Bailey & Lovie-Kitchin, 2013; Simons, 1983). Recently a new promising computerized tool with free access has been developed to assess acuity and crowding-limited size thresholds (Pelli et al., 2016). However, the tool requires some basic software and simple computer skills that may restrict its use in the clinical practice. As previously mentioned, many eye-charts are available for developmental use (Kay Pictures, Lea Symbols, Keeler/Teller cards, Cardiff Acuity test, Glasgow acuity cards, etc.). Nevertheless, only few and sparse normative reference data for children during development based on a large cohort are available (Pan et al., 2009; Salomao & Ventura, 1995; Saul & Taylor, 2015; Sheridan, 1974; Simons, 1983), and none with different levels of crowding.

Here we propose a new, easy to use, and free tool for measuring VA in different crowding conditions. The aims of this study were: 1) to verify the feasibility and the efficacy of this new tool for the measurement of crowded VA from developmental age to the entire lifespan; 2) to have a systematic description of the influence of VA with different level of crowding during the first grade developmental age.

2. Materials and methods

2.1. Participants

Participants were children recruited from a school screening performed in a primary school. Only children with written informed consent from their parents to take part in the study were enrolled. All participants were invited to use their glasses (if required) during testing. Exclusion criteria were: the forgetfulness of glasses normally used and binocular AV $> +0.3$ logMAR. A total of 252 children were selected, assessed and subdivided in: 1st grade (n = 95), 3rd grade (n = 87), 5th grade (n = 70). The study was carried out in accordance with the guidelines given in the Declaration of Helsinki, and the local ethical committee approved the procedure.

2.2. Stimuli

In order to assess VA with different inter-optotypes spacing, our newly Milan Eye Chart (MEC) was composed of three series of four VA eye charts, which were created using SLOAN letter optotypes with

100%, 50%, 25% and 12.5% inter-optotypes spacing. Three parallel charts were created for each level of spacing, with the same psychophysical characteristics but different sets of letters. These optotypes and layout has been shown to be comparable with the ISO 8596 standard optotype presentation (i.e., Landolt C), and also to be preferred by participants and faster to administer than the ISO standard (Engin et al., 2014; Koenig, Tonagel, Schiefer, Bach, & Heinrich, 2014). Taking into account the possible use during the lifespan, MEC charts were created using SLOAN font (https://github.com/denispelli/Eye-Chart-Fonts) in LibreOffice Draw package (https://www.libreoffice.org/). A standard Bailey-Lovie design was used (Bailey & Lovie, 1976). Each row was composed by five different Sloan letters from a set of 10 (C, D, H, K, N, O, R, S, V, Z) without repetition of adjacent letters along the horizontal and vertical direction. This arrangement follows the ETDRS charts that meet the recommendation of NAS-NRC (Ferris et al., 1982). The charts were created in a standard A4 format and printed in A4 sheets for far presentation at 3 m. The charts were composed of 11 lines of 5 letters each. The chart ranges from 0.7 logMAR to −0.3 logMAR of optotype dimension, with a progression of 0.1 logMAR for each line. The separation from one row to the subsequent was proportional to the dimension of the optotype of the first row and decreased over lines. Also, the inter-lines spacing was varied with 100%, 50%, 25% and 12.5%, together with the inter-optotypes spacing. The first series of charts were represented in Fig. 1. All twelve charts are available as online Supplementary Material. In developing the charts, we were aware that children deal better with symbols than with letter charts. Nevertheless, we focused on school grades where letters are well known, and their recognition is automatic. The children were all able to perform the measurements as shown in other studies (e.g., Engin et al., 2014).

2.3. Procedure

Testing was performed in a quiet room with no distractors, with an appropriate and diffused illumination (95 cd/m^2 that matches the requirements of ISO 8596). The charts were presented one by one at participants at eye level from a distance of 3 m. Each level of crowding was measured binocularly three times with the three different charts using a letter by letter VA testing procedure (Bailey, 2006) in a random order between the four levels of crowding. Letter by letter scoring provides a more precise measure of visual acuity (Ferris et al., 1982). The procedure of reading letters started from the bigger letters in the top row. Randomly, the examiner selected one letter from the second, third or fourth column. Participants were asked to read aloud the letters from top to bottom until they made an error. At this point, the examiner indicated the previous line and the participant was required to read aloud the entire line. When the size of letters approached threshold, the child was encouraged to guess until the errors were more than the correct read. To aid the testing procedure with young children, two examiners participated in the testing. One of the examiners explained the procedure and assisted the child. The second examiner was placed near the eye chart and indicated the column or lines that have to be read (not every single letter). Each VA score was assigned when the child read three out of five letters. The number of letters recognized was also recorded (3/5, 4/5 and 5/5) followed by a plus sign to indicate the number of letters read at the next smallest size (if correct, range 0–2). Subsequently, these scores were converted considering the entire line of five symbols. A minus was added when a single letter was missed from the entire line and a plus when a letter of the subsequent small size was read correctly. Then, at each letter was assigned a score of −0.02 and this value was added to the visual acuity score when the letter was read correctly and subtracted when the letter was missed (example: 0.1 3/5 + 1 was converted to 0.1–1 and then 0.12). Using this method, for each of the four levels of crowding three visual acuity scores were obtained. These values were averaged to have only four final scores, one for each level of crowding.

Statistical analyses were performed using a general linear model using repeated measure ANOVA and, when needed, paired comparisons were performed with Bonferroni correction. Effect sizes were reported as generalized eta squared. In order to assess the developmental trend, a series of regression analyses were performed, and all parameters of regression are reported in Table 1. Data were analyzed using R statistical environment and specific packages (R Core and Team, 2017).

3. Results

All children were able to perform the experimental procedure, with some differences in execution time for the youngest. Nobody has refused or withdrew from evaluation.

A mixed ANOVA was performed with the between factor *Grade* with three levels (1st, 3rd, 5th grade) and the within factor *Spacing* with four levels (100%, 50%, 25% and 12.5%). The results show significant effects for *Grade* [$F_{(2,249)} = 9.29$ $p < 0{,}0005$ $\eta^2_g = 0{,}06$], *Spacing* [$F_{(3,747)} = 933.8$ $p < 0{,}0001$ $\eta^2_g = 0{,}38$], and the interaction *Grade* × *Spacing* [$F_{(6,747)} = 8{,}5$ $p < 0{,}0001$ $\eta^2_g = 0{,}01$]. Post-hoc pairwise comparison with Bonferroni correction showed significant differences between grades 1st − 3rd and 1st − 5th for 50%, 25% and 12.5%, but no significant difference emerged for 100% spacing condition. Data are represented in Fig. 2.

To verify the relationship between grades and levels of spacing, a series of four regression models were performed using AV as a dependent variable and Grade as an independent variable. All values of spacing, excluding 100% showed significant slopes as a sign of developmental improvement. Regression data are reported in Table 1, and a graphical representation of results is shown in Fig. 3.

4. Discussion

We aimed to test the efficacy and feasibility of our newly devised Milan Eye Chart (MEC) for the assessment of VA in different crowding conditions during the lifespan, in particular during the developmental age. We obtained a systematic description of the change of acuity- and crowding-limited size thresholds in elementary school years (approximately from 6 to 7 to 11–12 years old). We follow the suggestions, made by Lalor et al. (2016), to measure VA and crowding with the same confounding optotypes, to place flankers closer than available instruments and to use simple VA charts. Our findings reveal a clear developmental trend for crowding limited acuity measure, while no improvement with age was found in standard acuity measurement (100% spacing).

4.1. Visual acuity

We aimed to measure VA for specific levels of crowding. The 100% spacing level represents a standard in VA measurement. Please note that this may not represent an uncrowded condition. Thus we call it large spaced chart. Subsequently, we tested 50%, 25% and 12.5% inter-optotype spacing as increasingly crowded conditions. Concerning 100% and 50% spaced charts, our results replicated those of Norgett and Siderov (2011) with no differences among grades with the maximum level of inter-optotype charts (100%), suggesting that AV development has already reached the plateau at 1st-grade primary school. Differences among grades emerged from 50% charts and lowered as a function of crowding.

Some authors have suggested to reduce the inter-optotypes spacing in VA charts in order to better screen amblyopia, increasing the crowding from 100% to 50% optotype spacing (Holmes & Clarke, 2006; Lalor et al., 2016) or more (Formankiewicz & Waugh, 2013; Song et al., 2014). MEC charts fit these requirements, but for completeness of diagnosis, a specific cut-off or full norms in children with refractively-correct would be required.

We acknowledge that the absence of a measurement of refractive status is a limitation of this study. Nonetheless, the evaluations of the

Fig. 1. Graphical representation of the four series of eye-charts used in the study. Top left: 100% inter-optotype spacing; top right: 50% inter-optotype spacing; bottom left: 25% inter-optotype spacing; bottom right: 12.5% inter-optotype spacing. The other two sets of four tables follow the same arrangement with different letter sequence.

Table 1
Regression parameters for the four crowding conditions separately.

	Intercept	SE	p-value	Slope	SE	p-value	R-squared
12.5%	0,2381	0,0106	< 0.0001	−0,0183	0,0033	< 0.0001	0,1116
25%	0,1603	0,01	< 0.0001	−0,0132	0,0031	< 0.0001	0,0675
50%	0,0939	0,0097	< 0.0001	−0,0097	0,003	< 0.005	0,0398
100%	0,043	0,0081	< 0.0001	−0,0049	0,0025	n.s.	0,0149

different crowding conditions were performed on the same subject in a within design. If the three groups would have shown different VA for different refractive status (i.e., myopia progression or amblyopia), we should have found a difference in a 100% spaced VA. The absence of this difference can be considered as a stable baseline condition for the other comparisons. The results show the validity of the proposed VA charts, which allow measuring crowding in children without sophisticated psychophysical set-up.

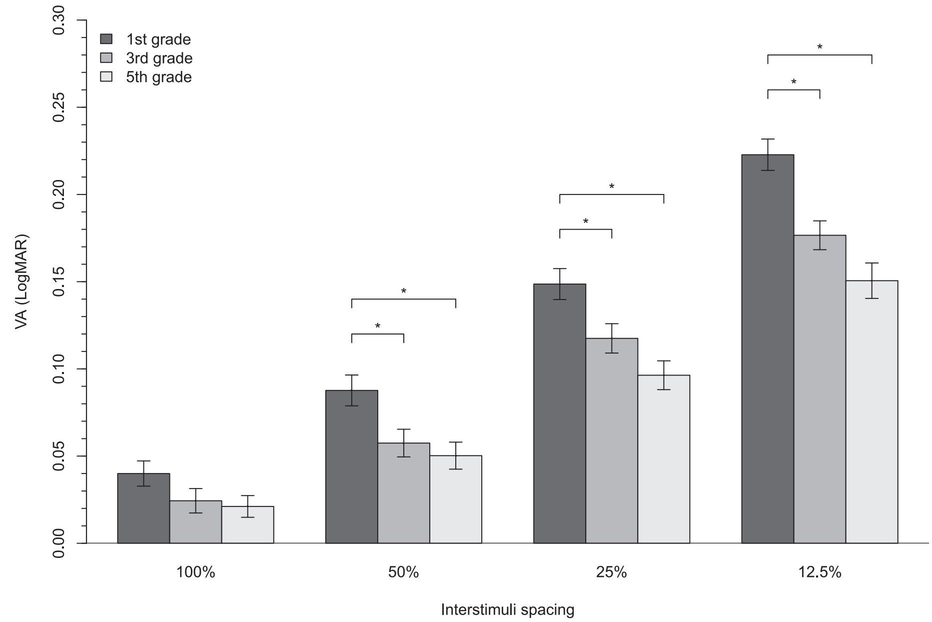

Fig. 2. Mean results of the experiment separated for crowding and grade. * = significant differences. Bars represent ± 1 SEM.

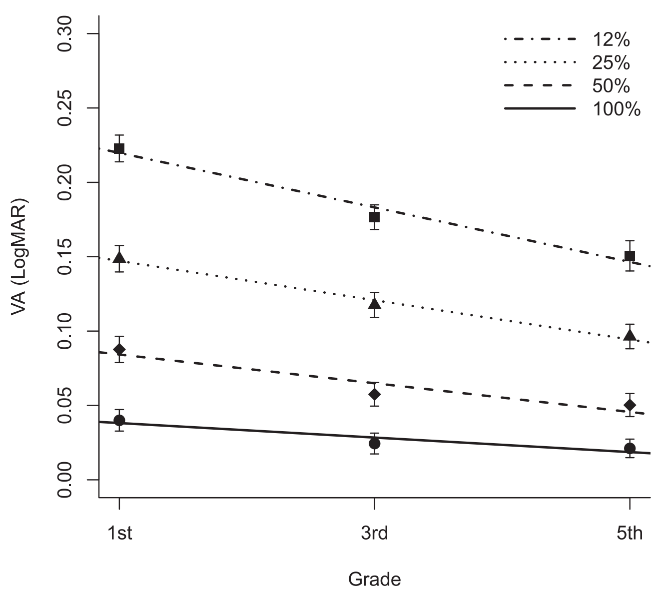

Fig. 3. Graphical representation of linear regressions for each level of crowding together with the mean result for each level of crowding and class. Bars represent ± 1 SEM.

Other eye charts are available for measuring VA in children with a controlled crowding condition [e.g., the Glasgow acuity cards (McGraw & Winn, 1993); the Cambridge crowding cards (Atkinson et al., 1988)] and these charts are very useful in the assessment of pre-schooler children. Conversely, for children in school ages and adults, the newly-designed MEC can overcome some limitations of the other tools while presenting several advantages: (i) The charts have a standardized and recognized design; (ii) They can be used from 1st class throughout all adulthood; (iii) There are different parallel forms; (iv) They provide similarity between flankers (not bars) and targets; (v) They present different levels of crowding, including a high level; (vi) They are easily portable, and no electronic instruments are required; (vii) The charts are freely available and can be printed on A4 sheets with near to zero cost.

4.2. Crowding

The different developmental trend of acuity with high spaced and low spaced eye-charts suggests that the mechanisms able to reduce crowding effects develop later compared to those responsible for VA. This result is in line with other studies showing that uncrowded VA is mature at an earlier age than crowded acuity (Jeon et al., 2010; Norgett & Siderov, 2011; Semenov et al., 2000). In fact, our data fits with those of Doron et al. (2015) who used stimuli and an approach very similar to ours, but with a very different procedure. The results showing that our youngest children display a VA similar to the oldest children with low crowding but lower with high crowding agrees with the idea that visual information processing is not entirely mature at those ages (Atkinson & Braddick, 1983; Doron et al., 2015).

In contrast, Bondarko and Semenov (2005) in their study in older children and adolescents (8–17) explained the different development of crowding and VA by the immaturity of the selective attentional mechanism. This explanation has also been proposed by Norgett and Siderov (2011) on the different factors underlying crowding development: gaze control and attentional factors. The attentional hypothesis is also coherent with the results, obtained on young adults, that foveal crowding is reduced by an optimal cue for focal attention (Albonico, Martelli, Bricolo, Frasson, & Daini, 2018). Overall our results, obtained with the MEC charts, converge with other studies (Bondarko & Semenov, 2005; Doron et al., 2015; Norgett & Siderov, 2011; Semenov et al., 2000). Between large spaced and narrow spaced conditions for measuring VA different spatial interaction effects as crowding and overlap masking are involved (Pelli et al., 2016; Song et al., 2014). Since the differentiation and the measurement of each effect requires specific psychophysical testing which is out of the scope of this study, we can only conclude that different effects co-occur to produce the results obtained. Various mechanisms are involved in the reduction of VA related to different levels of spacing. We are not able to confirm or disconfirm explanations in terms of the low-level immaturity of the visual information processing or lateral interactions from those of high-level such as attention or gaze control.

Along with the advantages presented above, we are aware that this study presents also some limitations. Firstly, there is a different level of crowding affecting the central three letters and the outers. The former is fully flanked by other similar letters, but the latter is free on one side (Song et al., 2014). Secondly, compared to other studies we have not measured single letter – uncrowded VA and general conclusions based on the comparison of pure VA regardless of crowding cannot be drawn. Nevertheless, as performed by Doron et al. (2015), a single presentation of letters could be simply implemented with MEC charts by using a series of masks over single isolated letters.

5. Conclusions

Using high-crowded VA charts, we found a different development of VA and crowding phenomenon in developmental age, with the latter that develops later. We tested the feasibility of high crowded VA charts, and we found that they can be used by school-age children and adults. During the lifespan, older adults also exhibit significantly slower reading speed and enlargement of crowding zone, suggesting that critical spacing increases with age (Liu et al., 2017). As a consequence, the VA charts proposed could also be used in detecting the change of crowding in older adults.

6. Disclosure

The authors report no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2019.01.003.

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