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Colour vision during the developing age

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Abstract

It has been previously shown [3-6] that chromatic discrimination across the life span is characterised by a bell-shape function that has its maximum at 20-30 years; after this age the ability to discriminate colours decreases due to age-related ocular and neuronal changes. However, it is unclear why the discrimination should also be poorer during the paediatric age range.

In this study we tested psychophysically if the elevated discrimination thresholds of a paediatric population reflect a real anatomical and/or functional visual development; or if they are biased by the difficulty in performing the discrimination task, and the attentional resources required to execute the test. We compared paediatric performance at two chromatic discrimination tests: the Universal Colour Discrimination Test (UCDT), and the Farnsworth-Munsell 100 Hue Test (FM100HT). The UCDT used a simple 2-alternative-forced-choice task to measure the minimum saturation required to discriminate the chromatic target from its achromatic background. Saturation thresholds were measured near the protan, deutan, and tritan confusion lines. Each threshold took about 2 minutes and was repeated twice for a measure of reliability. The FM100HT required the observer to sort a large number of caps according to their hue, and on average it took about 20 minutes to complete the test. The two tests were run on the same day and in random order.

We tested a population of 56 paediatric observers: 18 aged 5-6 years, 20 aged 9-10 years and 18 aged 13-14 years; all had normal colour vision, as assessed by either the Ishihara or the HRR plates. Our control group consisted of 18 adult observers aged 18-23 years; all had normal colour vision.

Expectedly, we found that the mean total error scores measured with the FM100HT dramatically varied with age. Surprisingly, chromatic discrimination thresholds measured with the UCDT were approximately constant across age for all confusion axes. In fact, apart from a few outliers, all paediatric observers showed chromatic discrimination thresholds that fell within the normal trichromatic range.

In conclusion, we found that chromatic discrimination in our paediatric population can be as good as chromatic discrimination in young adults, when assessed with a sensitive and fast colour discrimination test based on a simple task, like the UCDT.

Introduction

Human neonates see very poorly at birth, however their visual system undergoes to a continuous and rapid maturation during the first days, weeks and months of life. From an anatomical and physiological point of view, it has been shown that:

(i) Both rods and cones are present at birth but are immature in size and spacing [1].
(ii) The foveal maturation is not completed until approximately 6 months of age.
(iii) The optic nerve is almost full size at birth, but melination, which speeds the neural connection rate, is not complete until after age 2 years.
(iv) The lateral geniculate nucleus has full complement of neurons present at birth, but they enlarge and establish more connections to other neurons with age.
(v) The visual cortex has the adult number of neurons present at birth, but these are still migrating to the superficial layers of the cortex and forming their neural connections.

Functionally, these developmental changes seem to be correlated with:

(i) A poor visual acuity at birth, which improves rapidly during the first 6 months.
(ii) A band-pass spatial contrast sensitivity function (CSF) characterised by a lower peak sensitivity compared to the adults', and that occurs at a much lower frequency. During the development, the CSF appears to shift vertically (i.e. increase in sensitivity) and horizontally (i.e. extend the frequency range).
(iii) The temporal response function or critical flicker frequency (CFF) develops rapidly in infants. By 4 months, the temporal contrast sensitivity function is band pass like in adults, but the overall sensitivity remains low.
(iv) As shown by Teller and Palmer [2] dichromatic (tritanopic) colour vision is present by 2 months and trichromacy is present by 3 months of age.
(v) Both the photopic and scotopic luminosity functions in infants resemble those of adults.

These results have been collected by different studies using different techniques, however most of the information related to the functional performance has only become available in the past 40 years. This is because only recently traditional psychophysical methods developed for adults have been adapted to work with infants. For example, one of the most successful psychophysical techniques used with infants is the preferential looking technique first introduced by the American developmental psychologist Robert Lowell Fantz, and subsequently modified and extended by the American scientist Davida Teller to what is known today as the forced-choice preferential looking (FPL) technique.

In general, these studies show that the functional visual response of children becomes similar to the adults' around 5 years of age. Though, when it comes to colour vision, children show poorer chromatic discrimination compared to adults until their teen-age years [3-6]. To date, there is no unanimous consensus on what is causing this difference, which ferments the debate with various hypotheses. For example:

(i) Is the difference caused by continuous anatomical and/or functional developmental changes in vision, or by the ability to perform the discrimination task?
(ii) How much do children colour discrimination thresholds deviate from the adults' thresholds?
(iii) How should we interpret children's chromatic discrimination thresholds, as normal or anomalous?

The study described in the present paper was motivated by screening children potentially undergoing to clinical trials at UCL Institute of Ophthalmology and Moorfields Eye Hospital (London, UK). In a previous (unpublished) study, we found that when using the Fansworth-Munsell 100 Hue Test (FM100HT) with children without past history of ophthalmic diseases, we occasionally recorded scores as high as the ones obtained by children affected by visual dysfunctions. More interestingly, these two groups performed differently at a computerized colour discrimination test. Thus, in the present study we aimed to find out how much the colour discrimination performance depends on the test used, and how much on the colour discrimination ability of the children.

Methods

Observers

We tested 56 children and assigned them into three experimental groups according to their age:

- 18 children in the group 5-6 years
- 20 children in the group 9-10 years
- 18 children in the group 13-14 years

We also tested 18 adults aged 18-23 years, who represented our control group.

Experimental Protocol

The experimental protocol consisted of two phases: a screening phase and a testing phase. A schematic representation of the experimental protocol is illustrated in Figure 1. During the screening phase, all observers where tested using either of two standardized colour vision tests according to their reading abilities. In particular, children in the group 5-6 years were screened using the Handy Rand Rittler plates (HRR), while all the other observers were screened with the Ishihara plates. Only those observers who scored normally at either tests would take part to the testing phase. During the testing phase, observers were assessed using two colour discrimination tests: the Farnsworth-Munsell 100 Hue Test (FM100HT) and the Universal Colour Discrimination Test [7].

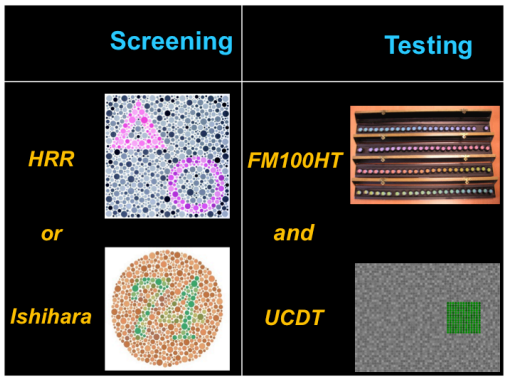


FIGURE 1. EXPERIMENTAL PROTOCOL.

THE FM100HT CONSISTS OF 85 CAPS ARRANGED IN 4 BOXES. TO ARRANGE THE CAPS TO FORM A GRADUAL TRANSITION IN TWO FIXED END-CAPS. PERFORMANCE IS MEASURED BY ERROR SCORE (TES), WHICH REPRESENTS THE NUMBER OF MISPLACEMENTS.

Figure 2 illustrates a child engaged in the FM100HT.

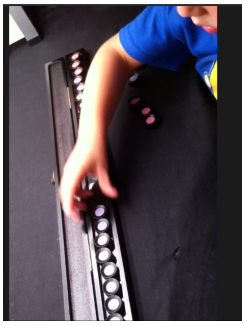


FIGURE 2. ILLUSTRATION OF A CHILD ENGAGED IN THE FM100HT.

FIGURE 3. ILLUSTRATION OF A CHILD PERFORMING THE UCDT.

The UCDT is a computerised test based on a simple 2-alternative-forced choice. The observer's task is to indicate the position of the coloured square-target. Figure 3 illustrates a child performing the UCDT.

Apparatus

The UCDT was displayed on a 22" NEC CRT, using ViSaGe (Cambridge Research Systems Ltd, Rochester, Kent) connected to a DELL computer. The monitor's spatial resolution was set to 1024 × 768 pixels at 120 Hz. A response box (Cedrus) was used to collect observers' responses. The test was programmed in MATLAB (MathWorks, Natick, MA, USA) with the support of the VSG software.

The protocol also included three conventional colour vision tests: the Ishihara plates (Ishihara's Tests for Colour Blindness, 38 Plates Edition, 1988, Kanehara & Co. Ltd, Tokyo, Japan), the Farnsworth-Munsell 100 Hue Test (X-Rite Inc., USA), and the Hardy Rand and Rittler (4th Edition) plates (Richmond products,

USA). These three tests were presented in a light booth (Pantone Color Viewing Light, Pantone Inc., U.S.A.) and were illuminated by the daylight simulator D50.

Calibration

The experimental monitor was characterised and its light output linearised using the ColorCAL colorimeter (Cambridge Research Systems Ltd, Rochester, Kent) and the automatic linearization procedure provided by the VSG software (Cambridge Research Systems Ltd, Rochester, Kent).

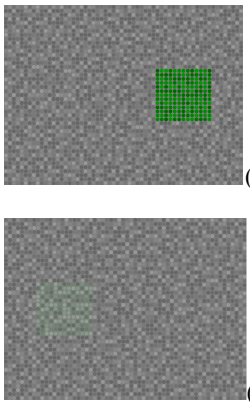
Stimuli

The stimuli of the UCDT consisted of a 36.18 × 27.13° background made of achromatic circles of random luminance with a small sub-set of them delineating an 8.58° square-target, as illustrated in Figure 4 (units are degrees of visual angle).The size of each individual circle was 0.48° and the distance between two adjacent circles was 0.035°. The target varied in saturation and hue close to the Protan, Deutan and Tritan confusion axes. The three hues were centred on the Equal Energy White point, with CIE (1931) chromaticity coordinates equal to (x = 0.333, y = 0.333)], which corresponded to (u' = 0.2104, v'= 0.4735) in the CIE 1976 chromaticity diagram. The luminance of all the circles varied randomly between 6 and 26 cd/m^2 in 6 steps and the foreground luminance was set to 18 cd/m^2.

Procedure

The experimental protocol always began with the screening phase, followed by the testing phase as described in the Experimental Protocol's section. During the testing phase, the tests were administered in random order, with breaks in between to allow the observers to take as many breaks as required. All tests where performed monocularly and with the observer's preferred eye.

During the UCDT, observers indicated whether the chromatic square appeared on the left- or on the right-hand side of the screen. Observers pressed one of two buttons to indicate the location of the square (a 2-alternative forced-choice judgment). On the following trial, the target saturation decreased if the answer was correct, or increased if the answer was incorrect. The stimulus was displayed on the screen for four seconds after which it was replaced by a uniform grey background until the answer was provided. In case of uncertainty, the observer was forced to guess. We used a weighted 1 up/ 1 down staircase with an up/down ratio of 1/3 in order to converge on the 75% threshold. Large, medium and small step sizes (Δ) were used, depending on the number of reversals completed. At the start of the staircase, the saturation was equal to the maximum length of the current axis that was within the colour gamut of the monitor; Δ was 0.2 until the first reversal; a Δ of 0.005 was used for 5 more reversals, and finally a Δ of 0.001 was used for the last four reversals. The mean of the last 4 reversals was taken as the saturation threshold, which represented the minimum saturation required to discriminate the target from the background.


(A)

(B)

FIGURE 4. SCHEMATIC REPRESENTATION OF THE STIMULI USED IN THE UCDT. IN (A) THE TARGET IS ON THE RIGHT, IN (B) THE DESATURATED TARGET IS ON THE LEFT.

Results

FM100HT results

Figure 5 illustrates the results obtained with the FM100HT for all observers. In general, we found that the mean total error scores (TES) varied with age which is consistent with previous results reported by [3], [5], and [6].

In particular, we found that the mean TES measured with the 5-6 year group were significantly different from all the mean TES measured in all the other groups, and that the mean TES measured in the 9-10 year group was significantly different from the adults mean TES ($p<0.000$). We found no significant difference between the mean TES measured in the 13-14 year group compared to the adults' mean TES ($p>0.05$).

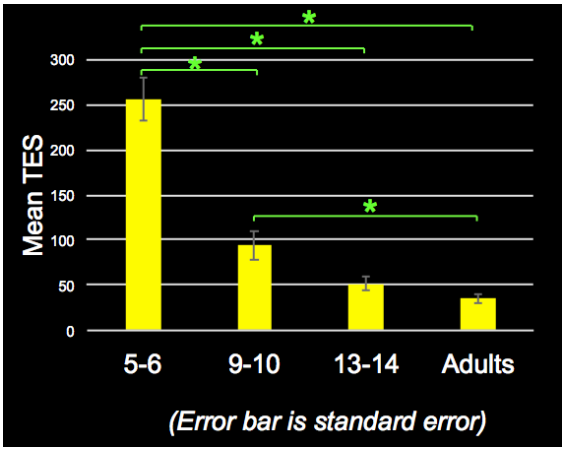


FIGURE 5. MEAN TOTAL ERROR SCORES (TES) MEASURED WITH THE FM100HT.

UCDT results

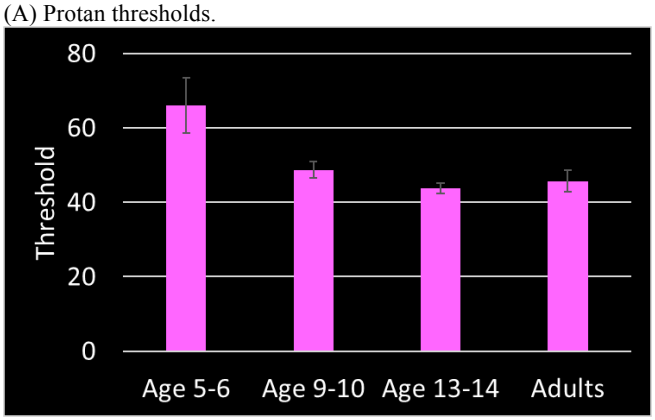
THE PROTAN, DEUTAN, AND TRITAN THRESHOLDS UCDT ARE REPORTED IN

Figure 6. We found that the thresholds measured in the 5-6 year group were significantly different from all the others ((p<0.000). In particular, a post-hoc analysis revealed a significant difference between the Protan thresholds versus Deutan thresholds (p<0.000) and the Protan thresholds versus the Tritan thresholds (p<0.000).
How should we interpret the higher Protan thresholds collected with the youngest group? Should they be considered as normal thresholds or anomalous trichromatic thresholds?
TO ANSWER THIS QUESTION, WE TOOK A CLOSER LOOK AT PLOTTED THE MEAN NORMAL TRICHROMATIC ADULT CONFIDENCE INTERVALS REPRESENTED BY ± 3 STANDARD DEVIATIONS.
Figure 7 illustrates the individual children's thresholds (coloured symbols) plotted relative to the normal adults' trichromatic range. The two red dotted lines define the confidence intervals of such range, whose mean is represented by the continuous red line. The continuous magenta, cyan and purple lines represent the mean thresholds along the Protan, Deutan and Tritan confusion lines respectively for each age group. Apart from a few cases, all the children thresholds fell within this normal trichromatic range.

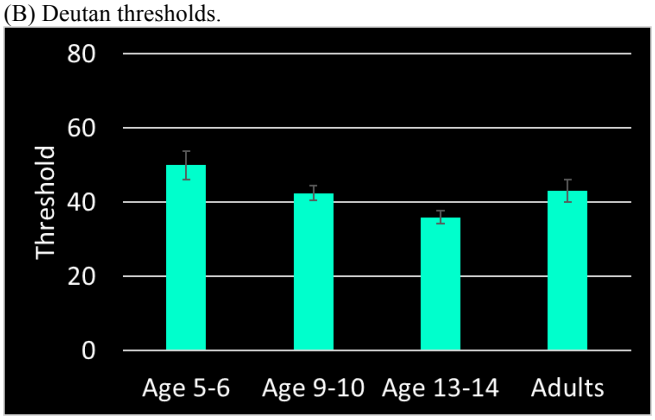
Conclusion

We have measured colour discrimination in children aged 5 to 14 years and compared their performance to the colour discrimination performance of adults.
We confirm that when colour discrimination thresholds are measured with the FM100HT, the performance varies with age and that children aged 5-6 and 9-10 are significantly different from adults.
However, the effect of age seems less obvious when measured with a simple task, like the one used in the UCDT.
In fact, with only few exceptions, all children thresholds fall within the normal trichromatic range.
This suggests that children's chromatic discrimination is nearly as good as adults' when measured with an easy task and a more sensitive sensitive test, like the UCDT.
It is possible that the higher chromatic discrimination thresholds obtained with the FM100HT are due to the complexity of the task and the relative longer duration of the test, which can severely compromise the attention spam of young children.
Recently, Cranwell and collaborators [6] investigated how general intellectual ability relates to colour discrimination on both the FM100HT and a computer-based chromatic discrimination threshold test. Consistent with our results, they found that adults' performance at the FM100HT was better than the performance of your children. Moreover, the latter was significantly positively correlated with nonverbal intelligence quotient (NVIQ) for all children groups. The authors conclude that: "The results indicate that FM100 performance is not purely a measure of color discrimination but instead also reflects general nonverbal ability".
The performance at the FM100HT is strongly affected by the ability of a child to execute a sorting task, their attentional resources required for a prolonged period of time, and their ability to review the caps' arrangement and correct possible misplacements. Because of these confounding factors, we believe that the FM100HT might underestimate colour discrimination ability in children aged 10 and under, and that other tests should be considered when assessing colour vision in the paediatric population.

(A) Protan thresholds.



(B) Deutan thresholds.



(C) Tritan thresholds.

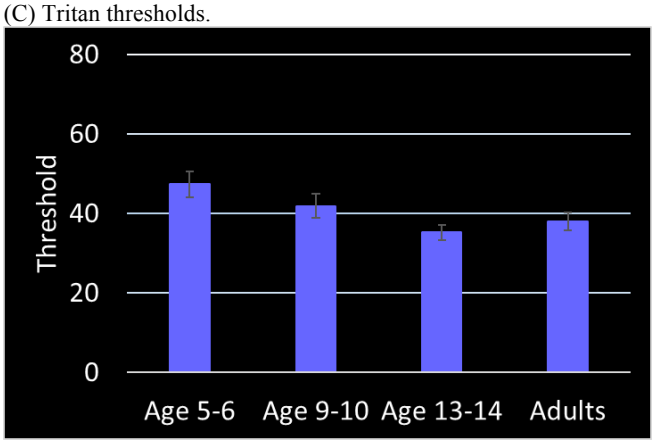
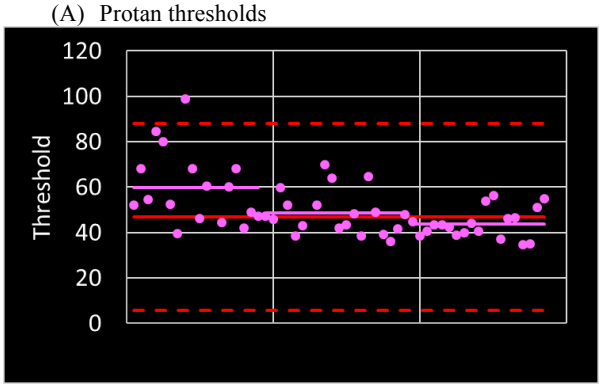
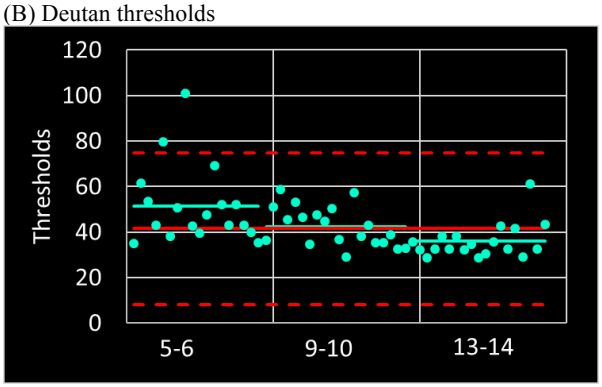


FIGURE 6. SATURATION THRESHOLDS MEASURED WITH THE UCDT. ALONG THE PROTAN, DEUTAN AND TRITAN CONFUSION LINES.

(A) Protan thresholds



(B) Deutan thresholds



(C) Tritan thresholds

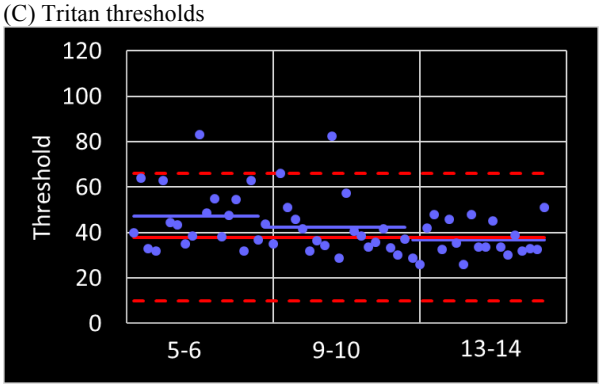


FIGURE 7. CHILDREN THRESHOLDS (SYMBOLS), MEAN (CONTINUOUS RED LINE) AND CONFIDENCE INTERVALS (DOTTED RED LINE) DEFINED ACCORDING TO THE NORMAL TRICHROMATIC RANGE DERIVED BY THE ADULTS' THRESHOLDS.

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Author Biography

Caterina Ripamonti received her BA in experimental psychology from the University of Trieste (Italy, 1996) and her PhD in vision science from the University of Derby (UK, 2002). Since then she has worked as a senior research fellow at the University of Pennsylvania (USA), the University of Cambridge (UK), and the University College London (UK). She is currently research scientist at Cambridge Research Systems and an honorary senior research fellow at the University College London and Moorfields Eye Hospital (UK).