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Performance on the Farnsworth-Munsell 100-Hue Test is significantly related to non-verbal IQ

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Abstract

Purpose. The Farnsworth-Munsell 100-Hue test (FM100) is a standardised measure of chromatic discrimination, based on coloured cap-sorting, which has been widely used in both adults and children. Its dependence on seriation ability raises questions as to its universal suitability and accuracy in assessing purely sensory discrimination. This study investigates how general intellectual ability relates to performance on both the FM100 and a new computer-based chromatic discrimination threshold test, across different age groups in both typical and atypical development.

Methods. Participants were divided into two main age groups, child (6-15 years) and young adult (16-25 years), with each group further subdivided into typically developing (TD; 3 groups; TD 6-7y, TD 8-9y, TD Adult) individuals and atypically developing individuals, all but one carrying a diagnosis of Autism Spectrum Disorders (ASD; 2 groups; ATY child 7-15y, ASD Adult). General intelligence was measured using the Wechsler Abbreviated Intelligence Scale and Wechsler Intelligence Scale for Children. All participants completed the FM100. Both child groups also completed a computer-based chromatic discrimination threshold test, which assessed discrimination along cone-opponent ("red-green", "blue-yellow") and luminance cardinal axes using a controlled staircase procedure.

Results. FM100 performance was better in adults than in children. Furthermore, performance significantly positively correlated with non-verbal IQ for all child groups and the young adult ASD group. The slope of this relationship was steeper for the ASD than TD groups. Performance on the chromatic discrimination threshold test was not significantly related to any IQ measure. Regression models reveal that chromatic discrimination threshold, although a significant predictor of FM100 performance when used alone, is a weaker predictor than NVIQ used alone or in combination.

Conclusions. The results indicate that FM100 performance is not purely a measure of colour discrimination but instead also reflects general non-verbal ability. Other measures of chromatic discrimination ability are therefore required for its accurate assessment, particularly in early or atypical development.

Introduction

Colour perception is a major contributing factor to a wide range of different behavioural tasks, including, for example: visual search[1] , object recognition[2] and evaluation of material properties (e.g. ripeness of fruit or healthiness of skin[3]). The low-level ability to discriminate between colours (chromatic discrimination ability) also underlies development of higher-level abilities and behaviours such as colour naming[4], affective responses to colour[5] and colour memory[6]. In recent years, colour perception has been increasingly studied in developmental disorders such as autism spectrum disorder (ASD) [7-9], Attention Deficit Hyperactivity Disorder[10, 11], and Williams Syndrome[12], as the extent of atypical sensory processing across all visual domains has become more evident in these disorders. It is therefore increasingly important to ensure that the diagnostic tools used to assess sensory processing, and in particular colour perception, are both sensitive and specific in isolating atypicalities in sensory processing. This requirement is complicated by the hypothesised relationship between sensory processing and intelligence[13, 14]; according to the original hypothesis of Galton and Spearman[13-15], higher intelligence is associated with better sensory discrimination abilities. The support for this hypothesis has been mixed[15-19], with low correlations found between general intelligence and some measures of sensory discrimination (including colour perception), and other more recent evidence[19] demonstrating a strong link between IQ and performance on a visual motion discrimination task. Nonetheless, the putative relationship makes it vital to ensure that tests of sensory processing are not confounded by direct contributions of general ability to performance.

The Farnsworth-Munsell 100-Hue Test[20] has been widely used by clinicians and visual scientists as a measure of chromatic discrimination ability[21] in both typically developing individuals with normal colour vision[22] and in individuals with congenital or acquired colour vision deficits[23-26] or developmental disorders[7, 8, 10, 12]. The FM100 test involves arranging a set of individual coloured caps of similar lightness and saturation in order between the hues of two fixed caps (e.g. blue and green), so that a smooth colour gradient is formed, with the hue differences between neighbouring caps as small as possible. The FM100 has been used in a wide range of ages, from early childhood (5 years) to elderly, and has the advantage of age-expected norms[22, 27]. It is also useful in identifying congenital and acquired retinal diseases and as a measure of lens yellowing during normal aging [28].

Other laboratory measurements of chromatic discrimination ability[29, 30], for example using detection tasks for forms defined by chromatic contrast embedded in backgrounds with dynamic random luminance variation, conclude that chromatic discrimination ability changes over the life span with sensitivity peaking in late adolescence/the twenties [31, 32] and subsequently decreasing throughout the remaining adulthood[22, 27, 33]. The improvement in FM100 performance with age up to

early adulthood, evident in studies that establish age-dependent norms[22, 27], is consistent with this age-related enhancement of chromatic discrimination ability. Yet other studies suggest that this change in FM100 performance may be due at least partly to improvements in the ability to perform seriation tasks[34, 35]. A recent study concludes that the general ability to perform a seriation task has sufficiently developed by the age of five that its further development does not explain the improvement in FM100 with age, but also that there are other non-colour-specific factors related to the difficulty of the discrimination which affect FM100 performance[36, 37] . It has also been observed that the Roth-28 (a shortened version of the FM100 using every third cap) is a time-consuming test that requires attention and a degree of visuo-motor competence, and is subject to learning and practice effects[38], and therefore the question has been raised as to whether other tests of colour discrimination might be more useful or appropriate[39]. Although a previous study concludes that the specific correlation between the FM100 and general intelligence is low[16], we have found (in a preliminary study to that reported here) that performance on the FM100 is related to non-verbal ability (NVIQ) in adults[9], and more strongly so in individuals diagnosed with ASD. Taken together, these results argue strongly for dissociating the various factors contributing to performance on the FM100 – including age, attentional ability, general intelligence, and chromatic discrimination ability - before accepting it as an unequivocal measure of chromatic discrimination ability suitable for widespread diagnostic use.

Here, the contribution of general cognitive ability to performance on two chromatic discrimination tests (the FM100 and a computer-based form-discrimination threshold task) is assessed. Specifically, we aim to determine the extent to which the relationship between non-verbal general ability and performance on the FM100 varies with age (e.g. between adults and children) and also with development, between typical and atypical development.

Methods

a) Participants

Ninety-two participants took part in the study, split across five different participant groups on the basis of chronological age (adult/child) and the typicality of their development (typically developing/atypically developing). All adult participants gave informed consent. For the child groups, parental consent was obtained and assent was given by the participant prior to the start of the experiment in line with the Declaration of Helsinki. Ethical approval was given from the Faculty of Medical Sciences Ethics Committee, Newcastle University (Approval Code:00618/2012; for child participants) and from the Newcastle University Psychology Ethics Committee (Approval Code 060004; for adult participants) .

There were two adult groups: a typically developing group (TD adult; n=28, mean age= 20.07 years, male=15, female=13) and an atypically developing group diagnosed with ASD (ASD Adult; (n=18, mean age=18.11, male=15, female=3). There were no psychiatric or developmental disorder diagnoses in the TD Adult group. Intelligence was assessed using the Wechsler Abbreviated Scale of Intelligence (WASI)[40]. Verbal IQ (VIQ) was determined by Vocabulary and Similarities subtests, and Performance or Non-Verbal IQ (NVIQ) was measured using Block Design and Matrix Reasoning subtests.

Three groups of children were recruited from local mainstream and special needs schools: two typically developing (TD) groups, 12 children aged 6-7 years old (TD 6-7y; male=5, female=7) and 19 children aged 8-9 years old (TD 8-9y; male=5, female=14); and one group of 17 children diagnosed with ASD plus one child with Williams Syndrome (ATY child; male=12, female=6). There were no developmental disorders reported for any children in the two TD groups. Four sub-tests of the Wechsler Intelligence Scale for Children (WISC[41]) Fourth Edition were administered as measures of IQ: Block Design, Picture Concepts, Vocabulary, and Similarities. NVIQ was determined by the combined scores on Block Design and Picture Concepts subtests. VIQ was calculated from the scores on Vocabulary and Similarities subtests. (See Table 1 for included participant demographics). All participants were screened for colour deficiencies using the Neitz Test of Color Vision[42] ; all included participants were classified as normal trichromats.

All participants were tested on the IQ tests described above and the Farnsworth-Munsell 100-Hue test (FM100) described below. Additionally, the three child groups (TD 6-7y, TD 8-9y, and ATY child) were tested on the chromatic contrast discrimination threshold test, described below. This test was developed for a children's colour perception test battery partly in response to the

observed relationship between performance on the FM100 and non-verbal ability (NVIQ) in adults[9] and was therefore not available at the time of the adult testing.

Results from six participants were removed from the FM100 analysis, for the following reasons: one ASD adult, one TD 6-7y child and two ATY child participants due to Total Error Scores of over 500, implying poor task comprehension[22]; one TD 8-9y child and one ATY child due to task non-completion (time constraints); one TD 8-9y child for deuteranomaly, as evidenced by Neitz Test screening and the FM100 error pattern. Table 1 reports indices for the remaining participants, whose FM100 results were included in analysis. On the chromatic contrast discrimination threshold test (see table S1), results were excluded from two ATY child participants due to task non-completion (time constraints), and from the one TD 8-9y child due to deuteranomaly.

Table 1. Participant group demographics, showing only participants whose results were included in the FM100 analysis (see text for explanation). Chronological age is shown in years. Verbal and Non-Verbal IQ are shown as standardised scores. In both adult groups, IQ was assessed using the WASI. In child groups (TD 6-7y, TD 8-9y and ATY child) IQ was assessed using the WISC Fourth Edition. Standard deviations are shown in brackets.

Group	Chronological Age	Verbal IQ	Non-Verbal IQ
TD Adult (n=28)	20.07 (2.04)	96.36 (10.47)	108.89 (9.23)
ASD Adult (n=17)	18.12 (1.22)	86.35 (19.05)	93.59 (18.94)
TD 6-7y (n=11)	6.37 (0.17)	111.45 (10.78)	109.27 (10.11)
TD 8-9y (n=17)	8.95 (0.31)	121.24 (11.84)	112.24 (13.79)
ATY Child (n=15)	12.06 (2.48)	71.4 (22.82)	85.53 (20.21)

b) Farnsworth-Munsell 100-Hue Test (FM100)

The Farnsworth-Munsell 100-Hue test [20] is a measure of chromatic discrimination. It consists of 85 coloured caps split across four trays. The caps vary only in hue, with lightness and saturation kept constant. Each tray has 21 removable intermediate caps (with the exception of the first tray where there are 22 caps) whose hues vary smoothly between those of the two fixed caps at either end. Standard administration procedures were followed: For each tray, the intermediate caps are removed from the tray and placed in a random arrangement while the participant looks away. The

participant is then asked to view and place the intermediate caps in the correct order in the tray between the two fixed caps, with as little difference in hue between neighbouring caps as possible. Standard prompts of, “Which colour is most like the one at the end?”, were used to ensure that the task was understood correctly. The trays were completed in different orders between participants. The order in which the participant placed the caps was recorded by the experimenter. The task was completed under simulated daylight illumination of colour temperature 6500K (D65) produced by a VeriVide D65 “Artificial Daylight” lamp.

Standard scoring procedures were followed. Error scores for each tray position are calculated on the basis of the differences between its chosen cap and the two neighbouring caps, generating a baseline score of 2 for each cap when in perfect order. Error scores for caps at the end of each tray were calculated using the neighbouring cap in the same tray and the first cap of the next tray, so that all caps are considered on a continuum around the colour circle. The Total Error Score (TES) is computed by first subtracting the baseline score from each tray position error score and then summing all 85 individual error scores. Specific anomalies of colour vision are revealed by specific error patterns (clustering of cap transposition errors along the protan, deutan or tritan axes).

c) Chromatic Contrast Discrimination Threshold Test (CCDT)

i) Overview

The Chromatic Contrast Discrimination Threshold (CCDT) was designed to isolate and assess discrimination within each of the cardinal chromatic mechanisms independently, similarly to the class of contemporary chromatic discrimination tests which include the Colour Assessment and Diagnosis (CAD) test [29] and the Cambridge Colour Test (CCT) [30]. It was developed for use in this and related studies of colour perception in children, with the requirements that it be engaging to children, portable, relatively quick to run, and easily reproduced without specialist equipment. The thresholds measured by the CCDT are comparable to those from the CAD and CCT, although exact comparisons cannot be made because of differences in the specific shape discrimination task used and the background chromaticity and luminance. The CCDT differs from the Farnsworth-Munsell 100-Hue test in that it directly measures thresholds for chromatic discrimination around a point of neutral chromaticity, whereas the FM100 does not measure thresholds but instead requires the observers to detect (and then seriate) chromatic differences between colours at a fixed distance from neutral chromaticity. These chromatic differences have been selected to be near threshold for normal observers (note that, in general, discrimination thresholds for hues of roughly equal

luminance and saturation will differ from thresholds relative to a neutral chromaticity). Despite the differences between the two types of test, other studies suggest that the age dependence for both is similar[33], supporting the assumption that both rely on the same basic chromatic processing mechanisms.

i) Apparatus and Setup

Colour stimuli were displayed on a computer screen placed at the back of a black viewing box (36cm x 44.8cm x 62.3cm). Participants rested their heads on a chin rest placed centrally at the front of the box and viewed the screen through an aperture (13.5cm x 9cm) placed 21cm along the box length, from a distance of 62cm. One of two different computer setups was used to control the experiment, depending on the group: for the TD 6-7y and ATY child groups, the experiment ran on a Dell Inspiron Laptop with stimuli displayed on its 14-inch screen; while for the TD 8-9y group the experiment ran on a custom built portable desktop tower, with standard components, running Windows 7 64-Bit edition with a PNY 600 10-bit graphics board with the stimuli displayed on a 10bit 23-inch Proart LCD monitor PA 238Q using a display port adapter. The same experimental programme (the Chromatic Contrast Discrimination Threshold test, or CCDT) was used for both setups, written in Matlab (v7.6.0, 2012b, The MathWorks, 2008, 2012), with graphics display functions from Psychtoolbox [43] and colorimetric conversion functions from *kccv* (a set of Matlab routines based on standard formulae [44] tailored for 8- or 10-bit displays appropriately); the 10-bit display used the NVIDIA QUADRO performance drivers. Spectral emission properties of both screens were characterised using a PR-650 spectroradiometer and colorimetric calibration tables were checked regularly using a Minolta CS-100 chromameter and updated when necessary to ensure colorimetric accuracy of the displayed stimuli.

ii) Stimuli

On each trial, a single coloured arrow (visual angle = 1.83^{o}), pointing either leftwards or rightwards, was presented. The vertical position of the arrow was randomly jittered from trial to trial 5.51^{o} above and below the central fixation point (visual angle = 0.92^{o}), on an achromatic grey background (CIE 1931 coordinates: x=0.36, y=0.37; Y=20.46 cd/m^2 for the 8-bit display; x=0.314, y=0.339; Y=64.8 cd/m^2 for the 10-bit display). The arrow colour was systematically varied in increments along only one of the three cone-opponent-contrast axes [45] (L-M or 'Red-Green'; S-(L+M) or 'Blue-Yellow'; L+M or 'luminance'; see supplementary material for further detail). The just-noticeable difference in arrow colour with respect to the background was calculated in ΔE units in a perceptually uniform colour space (CIE L*u*v* space).

iii) Design

A staircase protocol was used to vary the colour difference between the arrow and background on each trial, stepping through differences on each half of the red-green, blue-yellow and luminance cone-opponent-contrast axes separately, beginning with supra-threshold difference values and moving in progressively smaller increments to difference values that are just reliably detected by the observer. A one-up/two-down procedure was used, in which the participant must be correct twice consecutively to go down the staircase (i.e. testing smaller colour differences) whereas an incorrect answer will take the participant up the staircase (i.e. testing larger colour differences). (Details of step sizes are provided in the supplementary material). Each colour axis was tested in a separate block of trials, with a maximum of 100 trials per colour axis (50 for each colour direction of the axis; e.g. 50 each for “bluer” and “yellower”) and a maximum number of 30 reversals per half-axis, with the two independent staircases for each half-axis randomly interleaved in the one block. Each trial began with a 500ms centrally positioned white fixation dot, followed by the target which appeared for 150ms. The participant had to respond whether the arrow pointed to either the left of right, by pressing the corresponding mouse button. There was no time limit on the response, and the next trial began immediately after the response had been given.

iv) Procedure

Participants sat in front of the viewing box. Prior to the start of the experiment, the researcher checked that the participant understood the difference between left and right. A short practice set of highly visible arrows (with supra-threshold luminance contrast) was administered to check that the participant understood the experiment. After the practice set the actual experiment began. In a game-like format, participants were presented with a choice for each condition (each depicted by a different storybook image) and performed each condition only once. The order of condition was not counterbalanced but there was no significant difference of order for any of the groups (lowest $p=0.11$). Each colour-axis condition ran until either the maximum number of trials or maximum number of staircase reversals was reached. Once each condition had finished the participant was given a short break before continuing to the next condition. All conditions were either completed in one session or over two sessions.

Results

Experiment 1: Farnsworth-Munsell 100-Hue Test Results

The error patterns of all included participants revealed no specific anomalies of colour vision. A one-way ANOVA conducted with Total Error Score (TES) as the dependent variable and a between-subjects factor of participant group found a significant difference in TES between groups, F (4, 83) = 11.83, p<0.001 (see figure 1). Subsequent post hoc t-tests using a Bonferroni-corrected p-value revealed specific group differences: the TD adult group had significantly lower TES (mean TES = 45.79) than all other groups (highest p<0.001) and the TD 8-9y group had significantly lower TES (mean TES = 112.47) than the ATY child group (mean TES =209.47), t(30)=-3.16, p<0.05 (TD 6-7 group mean TES = 197.64; ASD adult group mean TES = 123.29). No other specific group TES comparisons revealed significant differences (lowest p=0.115).

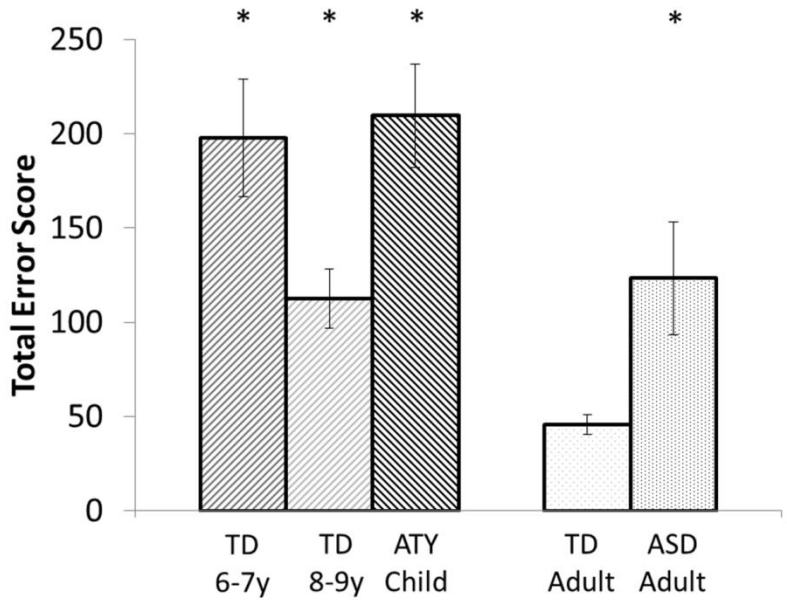

Figure 1 – Total Error Scores (TES) for the FM100 for each participant group. Higher TES reflects poorer performance on the test. Errors bars are +/- one standard error. The * denotes a significant difference from the expected age-appropriate norms reported by Kinnear & Sahraie (2002).

a) Correlation of IQ with TES

Correlations were calculated for each group between TES and standardised scores on VIQ and NVIQ subscales of respective IQ tests. For VIQ and TES correlations, significant correlations were found for ASD adult (r=-0.68, p <0.005), and ATY child groups (r=-0.58, p<0.05). No other VIQ/TES correlations were significant (lowest p=0.33). For NVIQ correlations with TES there were significant correlations for ASD adults (r=-0.89, p<0.001), TD6-7y (r=-0.63, p<0.05), TD 8-9y (r=-0.65, p<0.005), and ATY child groups (r=-0.62, p<0.05) (see Figure 2). A trend towards significance was observed for the TD adult group (r=-0.32, p=0.095).

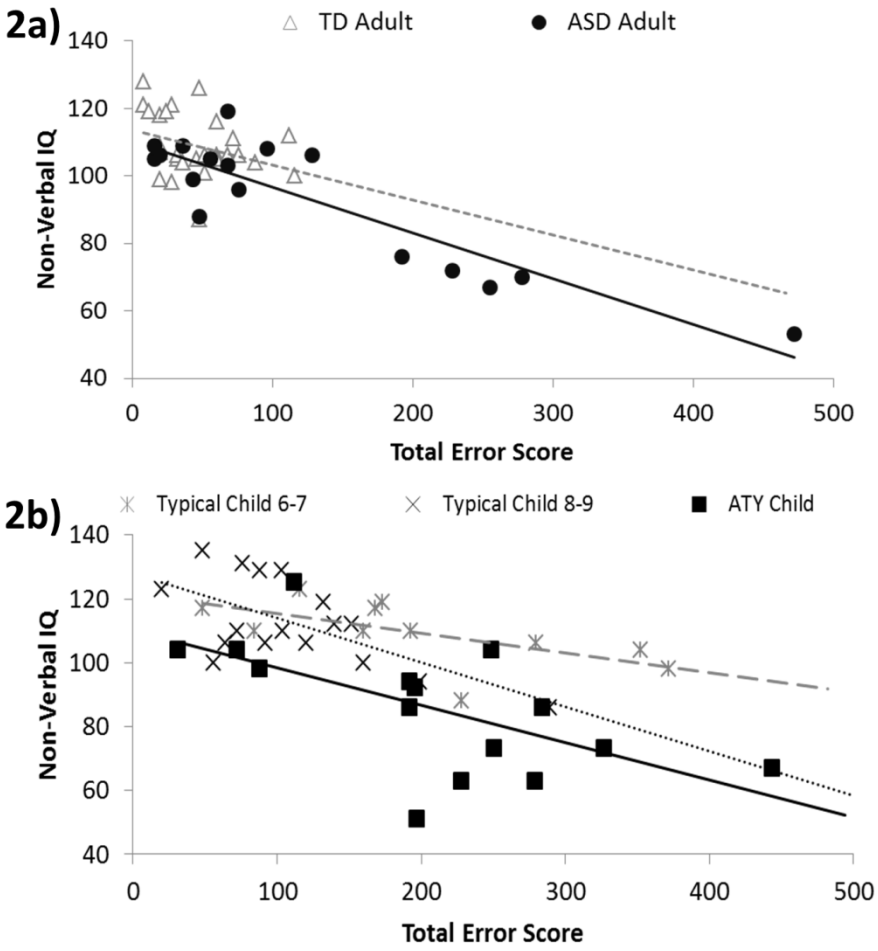

Figure 2 – Individual standardised NVIQ scores plotted against FM100 Total Error Scores. Lines are least-squares best fits for each group. In both graphs, ASD groups are represented by filled shapes and solid lines. (a)Adult groups: The TD adult group are denoted by unfilled triangles and the ASD adult group by filled black circles. (b) Child groups: The TD 6-7y group are denoted by grey asterisks*, the TD 8-9y group by grey crosses, and the ATY child group by filled black squares.

b) Relation to previously reported age-norms

Comparisons between the TES found in this sample and expected age-norms[22] were made. Difference scores between observed and expected scores for every participant were calculated, with a negative score indicating worse performance relative to the expected age score and a positive score better performance (see figure 1). One-sample t-tests were conducted against a value of 0 to reveal any significant deviations in each participant sample relative to expected age norms. Significantly better than expected performance was found in the TD 6-7y, $t(10)=2.81$, $p<0.05$ and TD 8-9y, $t(16)=2.4$, $p<0.05$, groups and significantly worse than expected performance for the ASD adult, $t(16)=2.65$, $p<0.05$, and ATY child, $t(14)=-3.65$, $p<0.005$, groups. No significant differences with age-expected norms were found for the TD adult group, $t(27)=1.02$, $p=0.32$.

a) Discrimination thresholds on chromatic and luminance axes

Individual staircases for each colour half-axis were analysed for convergence and excluded from further analysis if either of two conditions were met: (a) no reversals in the final 20% of trials or (b) final stimulus contrast less than or equal to zero, relative to background chromaticity. If the staircase for one half-axis did not meet these conditions, the staircase in the other half-axis was also discarded from analysis. For any one axis (Red-Green (R-G), Blue-Yellow (B-Y), or luminance (LUM)), a maximum of 6 participants' staircases were excluded on these criteria for the ATY child group, and a maximum of 3 were excluded for the TD 6-7 child group. All staircases in the TD 8-9y group were accepted. All participants described in Table S1 in the supplementary material contributed acceptable data for at least one axis.

Threshold contrasts for each of the six half-axes were calculated in ΔE_{uv} units, as described above. The two thresholds for the two directions for each condition were then averaged together to give an overall threshold for each cardinal axis (e.g. blue and yellow individual thresholds were averaged together for a B-Y axis threshold). To normalise the threshold distributions for each colour axis, ΔE_{uv} thresholds were converted to a logarithmic scale.

To compare thresholds between colour axes, data collected from the 8-bit display (TD 6-7y and ATY child groups) and 10-bit display (TD 8-9y child group) systems were analysed separately, given the difference in background luminance between the systems, which affects the absolute magnitude of the thresholds. For the former, a two-way ANOVA with participant group (TD 6-7y/ ATY child) and colour axis as fixed factors and threshold (ΔE_{uv}) as dependent factor revealed a significant main effect for colour axis, $F(1,56)=15.78$, $p<0.001$. Post-hoc tests revealed that

thresholds were significantly lower for the luminance than both R-G and B-Y colour axes for both TD 6-7y (highest $p<0.001$) and ATY child groups (highest $p<0.001$). There was no significant difference between R-G and B-Y thresholds for either group (lowest $p=0.329$). A significant main effect was also observed for group, $F(1,56)=15.781$, $p<0.001$. Post-hoc tests conducted for each colour axis further revealed significant differences between groups on the B-Y axis, $t(19)=2.93$, $p<0.05$, with thresholds significantly higher for the ATY vs TD 6-7y child groups, but not for luminance ($p=0.22$) or R-G axes ($p=0.19$).

Similarly, for data from the TD 8-9y child group, a two-way repeated-measures ANOVA with a within-subjects factor of colour axis (3 levels) revealed a significant main effect of axis , $F(2,34)=39.46$, $p<0.001$, with luminance thresholds significantly lower than both R-G, $t(17)=12.9$, $p<0.001$, and B-Y, $t(17)=6.18$, $p<0.001$, thresholds. R-G and B-Y thresholds did not significantly differ from each other, $t(17)=1.6$, $p=0.13$.

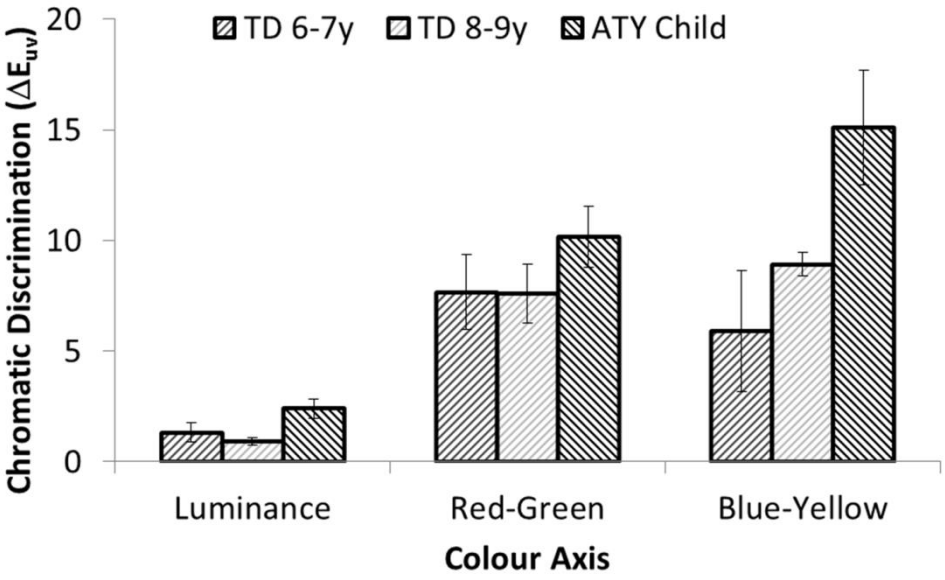

Figure 3 – Average discrimination thresholds for the luminance, red-green and blue-yellow colour axes, as determined by the Chromatic Contrast Discrimination Threshold test. The three groups (TD 6-7y, TD 8-9y, and ATY child) are indicated by different diagonal line shading, as shown in the legend. Error bars indicate standard errors.

c) Correlations of Thresholds with IQ

Correlation analyses were conducted to reveal relationships between VIQ and NVIQ and discrimination thresholds on the three colour axes, using adjusted p-values to control for multiple comparisons. No significant correlations were found in any participant group for either VIQ (lowest p=0.18) or NVIQ (lowest p=0.22).

d) Correlations between FM100 and Chromatic threshold

Correlation analyses were conducted to examine the relationship between performance on the FM100 and CCDT tests. Performance was again split via participant group. For the CCDT test, the mean chromatic discrimination threshold was calculated by averaging the B-Y and R-G thresholds. No significant correlation was found for the TD 6-7y child group (p=0.73). A significant correlation for the ATY child group was found (r=0.83, p<0.001), while a trend towards significance was revealed for the TD 8-9y child group, r=0.44, p=0.08.

Regression Analysis

To further assess the role of possible factors on FM100 performance, a multiple regression was carried out to estimate the extent to which performance on the FM100 might be predicted by NVIQ, chronological age and chromatic discrimination (as measured by the average B-Y and R-G thresholds from the CCDT test. This was done to gain an overall measure of chromatic discrimination to make this analogous to the TES on the FM100). Four predictors were included in the model: NVIQ, chronological age, development typicality (Typical/Atypical) and chromatic discrimination threshold. The analysis included only participants who completed both the FM100 and the CCDT test, from all child groups. Predictors were entered into the regression model using the backward entry method, appropriate in the absence of an *a priori* theory for which predictors would explain the most variance in FM100 performance. From this procedure, two models were generated. Model 1 included all of the variables, while Model 2 included all variables except for participant group (development typicality) since this factor was found not to be a significant predictor (see Table 2). Overall, both models significantly explained substantial variance in FM100 performance: Model 1 explained 53.2% of the variance, $F(4,30)=8.54$, p<0.001 while Model 2 explained 53.1% of the variance, $F(3,31)=11.70$, p<0.001. Additional regression models run on data from all participant groups alone and in combination are described in the supplementary materials; in all models, NVIQ is always the highest predictor, and although CCDT thresholds are significant predictors when used solely, they explain much less variance than NVIQ-only models.

Table 2. Backward stepwise regression model for the contributions to FM100 performance of distinct factors: NVIQ, chromatic discrimination, chronological age and development typicality. Model 1 includes all of the predictor variables; Model 2 omits only development typicality. The symbols *, **, *** denote significance at $p<0.05$, $p<0.01$ and $p<0.001$ respectively.

	Model 1			Model 2		
Variable	*B*	*SE B*	β	*B*	*SE B*	B
NVIQ	-3.629	0.953	-0.737***	-3.743	0.859	-0.76**
Chromatic Discrimination	236.143	106.66	0.369*	231.364	103.896	0.361*
Chronological Age	-1.9	0.769	-0.557*	-1.767	0.614	-0.518**
Development	13.69	46.23	0.064			
R^2		0.532			0.531	
F-value		8.539			11.701	

Discussion

The major finding in this study is that non-verbal general ability differentially affects participants' performance on two different chromatic discrimination tasks. The results from experiment 1 show that performance on the FM100 is significantly associated with non-verbal ability in all groups except typically developing adults. Furthermore, this association is stronger in children, and even stronger in atypically developing individuals (the majority with ASD). The results from experiment 2 demonstrate, conversely, that this association between general ability and colour perception in the younger age groups does not hold for the computer-based chromatic discrimination threshold test (CCDT).

The results therefore strongly suggest that the FM100 is not an unequivocal measure of colour discrimination but conflates this with a measure of "non-verbal ability", providing evidence for previous suggestions that cognitive factors unrelated to chromatic discrimination ability influence performance on the task[9, 37]. The FM100 performance-NVIQ correlation slopes are steeper and more significant in the child groups than adult. Furthermore, the results of the regression model suggest that non-verbal ability is a significant predictor of performance in addition to age and the ability to discriminate between colours.

When considering why the FM100 is associated with general cognitive ability but the chromatic discrimination threshold test is not, the relative task demands are important. Successful performance on the FM100 requires attentional and visuospatial abilities in addition to chromatic discrimination ability. Spatial comparisons are required between the selected and non-selected caps. Attention switching between the local field – in making a comparison between two adjacent caps, and the global field - in overseeing the entire colour gradient - is also essential for good performance. These task demands may be influenced by different factors in each group. In typically developing children competency of global processing does not develop until late into childhood[46]. Individuals with ASD are more likely to process visual information locally rather than globally [47] and to have difficulty switching between local and global processing[48]. Non-verbal ability may also differentially affect performance between groups. Better performance in the older TD groups may reflect more mature global processing competency than in the younger TD groups. Poorer performance in the ASD groups may be the result of difficulty both in sustaining and switching of attention between local and global fields of the FM100.

These results have implications for the FM100 norms that have previously been reported[22]. These norms implicitly assume that performance is unrelated to IQ and that task demands are consistent between different ages. In the current study, both TD child groups are above average in non-verbal ability and perform significantly better than expected from the Kinnear and Sahraie (2002) norms[22]. Given that the number of participants in both studies is similar for each respective age group, this comparison calls into question the reliability of the norms for these age groups and more so for the younger age groups for which the number of observers is even smaller (e.g. 9 observers for age 5 years)[22]. These results, combined with those from a preliminary study by Hurlbert and colleagues [9] instead suggest that caution must be exercised when using FM100 norms, for all ages, but especially for younger children or clinical populations where the NVIQ is lower than average with respect to chronological age, given that the relationship between FM100 performance and NVIQ is stronger for groups of the latter type.

In comparison to the FM100, the CCDT has fewer task demands. This test of chromatic discrimination requires attention on a trial-by-trial basis only to identify the direction of an arrow. Like other standardised tests in whose class the CCDT falls (e.g. the CCT [30]and the CAD [29]), the CCDT measures discrimination thresholds along isolated chromatic directions away from a fixed adaptation point. Although other colour discrimination tasks have been adapted for use with children (e.g. the CCT [49]), to our knowledge these have yet to be demonstrated as independent of general ability. Other standardised chromatic discrimination threshold tests call on more complex

aspects of visual processing which may introduce additional confounds when used in children: the CCT[30], for example, requires participants to identify a global shape composed from local elements while the CAD (or City Colour Vision Test[50]) requires participants to discriminate the direction of a moving stimulus[29, 50]. The former thus presents a potential confound in distinguishing between deficits in local chromatic discrimination vs global shape processing, while the latter may be unable to dissociate between deficits in motion direction discrimination vs chromatic discrimination, which are known to develop at different rates in children [33, 51] The CCDT task used in this study may provide a more direct measurement of chromatic discrimination by being a simple shape identification task, which requires only a coarse binary judgement of left versus right, does not depend on numeracy or literacy skills, and does not involve a trade-off between local and global processing, involving the discrimination of only a single large shape against a uniform background. Performance is more likely to be independent of developmental stage or cognitive ability, allowing for age variations in chromatic discrimination to be more accurately captured. Because participants continue the task only until they reach their own individual threshold, task difficulty also remains constant between individuals even though other factors such as chronological age or chromatic discrimination ability may differ between participants. Because of their shared properties, we would expect CCDT performance to share the same pattern of age dependence as that demonstrated for the CCT and CAD[32] , and our ongoing studies support this expectation.

Although we have here carried out the CCDT only in the younger age groups and therefore demonstrated this independence only for those groups, we would expect the independence to hold for the adult groups also, particularly given their better chromatic discrimination ability, higher absolute IQ, and increased attentional capacity relative to children[52].

It is not possible from this study to address specifically whether sensory processing is related to general ability, as suggested by other studies[13, 19]. Nonetheless, the results here do highlight the importance of using multiple tests within the same sensory processing domain when assessing this link. For example, the results of the FM100 alone would suggest that there is a link between sensory (chromatic) discrimination and intelligence, while the results of the CCDT test alone would suggest that there is no such relationship. The differential correlation between non-verbal ability and the FM100/CCDT test demonstrate that different tests measuring the same sensory (chromatic) discrimination may give different results depending on the different task demands. In order to more accurately tease apart the possible relationship between intelligence and sensory discrimination, comparisons need to be made on performance from multiple tests measuring the same sensory domain.

In summary, we show that general ability affects performance on two different colour discrimination tasks differently: performance on the FM100 is associated with non-verbal ability while the chromatic contrast discrimination task is not. This result impacts upon the appropriateness of the clinical use of the FM100. The results from this study suggest that the use of an appropriate psychophysical task which has fewer task demands and is of equal difficulty across all ages will give a more accurate measure of colour discrimination and ultimately visual function in participants.

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601 **Supplementary Information**

602 **Farnsworth-Munsell 100-Hue Test Results**

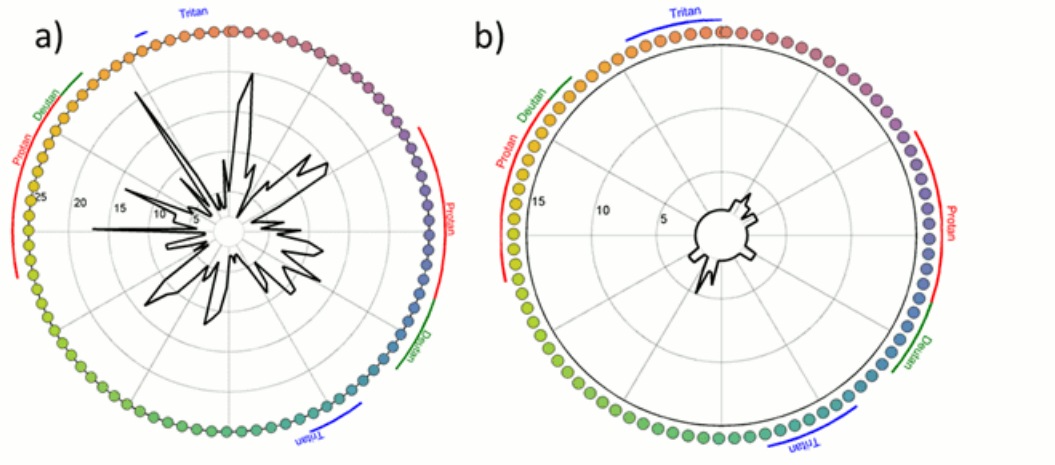

Figure S1. Sample Farnsworth-Munsell 100-Hue error plots for two participants. Error scores at individual cap positions around the hue circle are represented by radial distance of the black contour from the centre. The error scale, shown by labels on concentric grey contours, differs in the two plots. a) Results for a participant from the ASD adult group, who performed below average on the FM100 (FM100 Total Error Score = 472; NVIQ standard score = 53, below average). b) Results for a participant from the TD adult group who performed above average on the FM100 (FM100 Total Error Score = 28; NVIQ standard score = 121, above average).

Chromatic Contrast Discrimination Threshold Test (CCDT)

Table S1. Participant group demographics, showing only participants whose results were included in the CCDT analysis. Chronological age is shown in years. VIQ and NVIQ are shown as standardised scores. In all groups IQ was assessed using the WISC Fourth Edition. Standard deviations are shown in brackets.

Group	Chronological Age	VIQ	NVIQ
TD6-7y (n=12)	6.38 (0.17)	113.33 (12.17)	107 (12.45)
TD8-9y (n=18)	8.96 (0.31)	121.94 (11.87)	112.83 (13.61)
ATY Child (n=16)	12.15 (2.42)	71.25 (22.05)	85.13 (19.59)

Stimuli: The contrast of the arrow stimulus with respect to the background was calculated in cone-opponent-contrast coordinates following the formulae given in Eskew et al. (1999). The origin of this coordinate space is given by the cone excitations to a reference white surface (L_0, M_0 and S_0), in this case, the uniform grey background, using the Smith-Pokorny (1975) cone fundamentals.[1] Cone

excitation values for the arrow are defined with respect to this origin by the ratios: $\Delta L = (L - L_0)/L_0$, $\Delta M = (M - M_0)/M_0$ and $\Delta S = (S - S_0)/S_0$, where L, M, and S are the cone excitations to the arrow stimulus. The cone-opponent contrast coordinates of the arrow stimulus are then calculated for each of three axes:

$$LUM = [0.78*\Delta L + 0.37*\Delta M];$$

$$RG = [0.7*\Delta L - 0.72*\Delta M + 0.02*\Delta S];$$

$$BY = -[0.55*\Delta L + 0.25\,\Delta M - 0.8\Delta S];$$

where *LUM* is the luminance axis, *RG* is the "red-green" axis and *BY* is the "blue-yellow" axis.

For each half of each axis, a set of displayable colours (numbering on average 75) were calculated whose colour differed from the uniform background only along that axis, in the smallest increments achievable for the given display device. For example, for the "yellower" direction of the BY axis and the 10bit display, all ~65 stimuli had effectively the same LUM and RG coordinates as the grey background while their BY coordinates varied systematically from the background BY coordinate in steps equal to (on average) 0.3142 ΔE_{u*v*}, up to a maximum difference of approximately 20 ΔE_{u*v*}. (The unit ΔE_{u*v*} is defined as a just-noticeable-difference in the perceptually uniform CIE Lu*v* space.)

Staircase Procedure: Six individual staircases, one for each direction of each colour axis (i.e. each half-axis), were completed by each observer. Each staircase drew its stimuli from one of the colour sets calculated as described above. Each colour axis was tested with a separate block of trials, in which the two half-axis staircases were interleaved; e.g. for the BY colour axis, the "bluer" and "yellower" staircases were interleaved. Within each half-axis staircase, the arrow colour was varied in 6 decreasing step sizes ranging from approximately 10 ΔE_{u*v*} to 0.3 ΔE_{u*v*} (for the 10-bit

experiment; step-sizes ranged from approximately 10 $\Delta E_{u^*v^*}$ to 0.8 $\Delta E_{u^*v^*}$ for the 8-bit experiment) in a one-up/two-down procedure. The steps were selected in terms of the indices of the colour stimuli in the colour sets described above, with the smallest step in each case corresponding to an index step-size of 1.

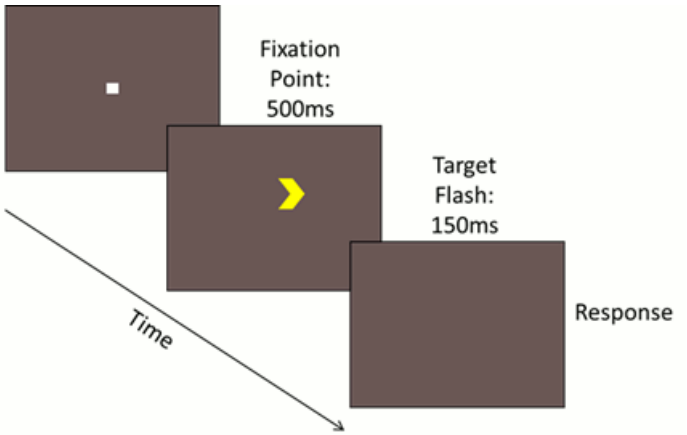

Figure S2. Schematic illustration of stimuli in the CCDT, and the temporal sequence of an individual trial. Sizes of stimuli are not to scale.

Comparison of 8-bit and 10-bit display systems for CCDT

In this paper, the CCDT was used with two different graphics boards/display systems (8-bit and 10-bit), due to changes in equipment availability over the course of the study. Although the 10-bit system is preferable for widespread use because of its higher chromatic resolution, the two systems are equally effective for the populations studied here. A control experiment in 5 adult individuals, who performed the test on both 8-bit and 10-bit systems in the same day, revealed a significant positive correlation between thresholds on the two systems ($r = 0.88$; $p < 0.001$). All thresholds obtained on the two systems are also comparable to thresholds reported for other standardised chromatic discrimination tests, e.g. the Colour Assessment and Diagnosis (CAD) test[1] and the Cambridge Colour Test (CCT)[2], in both absolute magnitude and variation across chromatic direction. Note that because thresholds vary across colour space, with both the background chromaticity and luminance, it is not appropriate to make exact comparisons.

Regression Model

Further regression models were run on data from all participants (child and adult groups), using TES as a dependent variable and NVIQ, VIQ, Chronological Age (months), and Development as predictors, excluding CCDT (Backwards entry method). Three iterations of model yielded the following predictions:

1) R^2=64.9%, all predictors included

2) R^2=64.9%, Development only removed

3) R^2=64.3%, Development and VIQ removed (only NVIQ and CA remaining)

NVIQ is always the highest predictor, but with slightly lower weighting than in results from Model 2 presented in Table 2 of the main paper. A similar final regression model run for the child groups only (with NVIQ and Chronological Age only as predictors after Development and VIQ have been removed) yields R^2 of 47.1%. For the adult groups only, the final regression model explains 66.9% of the variance (with NVIQ only as predictor, after Development, VIQ and Chronological Age have been removed).

All models explain more variance when not including CCDT measures. For data from the child groups only, CCDT thresholds (converted to logarithms) are a significant predictor when they are the only predictor but explain much less of the variance (23.4%) than the NVIQ-only model (39.5%). For data from both the child and adult groups, the NVIQ only model predicts slightly more variance (41.4%). The adult only NVIQ only model predicts much of the variance (66.9%).

Regression models were also run using the CCDT threshold from each colour axis separately with its corresponding FM100 partial error score (PES), for example, using only the Red-Green PES and Red-Green CCDT thresholds within one regression analysis and the Blue-Yellow PES and Blue-Yellow CCDT thresholds in a separate analysis. The final Red-Green model explained 44% of the variance (final model predictors: Development, Red-Green CCDT threshold and NVIQ). The Blue-Yellow model explained more of the variance (61.3%, final model predictors: Chronological Age, Blue-Yellow CCDT threshold and NVIQ) than the Red-Green model. Despite the difference in overall variance explained

between the Red-Green and the Blue-Yellow model, NVIQ was still the highest loading predictor in both models.

A final regression analysis was done using Development, Chronological age, NVIQ, Red-Green CCDT threshold and Blue-Yellow CCDT threshold as predictors and FM100 TES as a dependent variable. Five iterations of the model yielded the following predictions:

1) R^2= 54.8%, All variables included
2) R^2= 54.8%, Development removed
3) R^2= 52% , Blue-Yellow CCDT threshold removed
4) R^2= 47.8% Red-Green CCDT threshold removed
5) R^2= 43.3% Chronological Age removed (Only NVIQ remaining).

1 Smith VC, Pokorny J. Spectral sensitivity of the foveal cone photopigments between 400 and 500 nm. *Vision Research* 1975; 15:161-171.
2 Birch J, Barbur JL, Harlow AJ. New method based on random luminance masking for measuring isochromatic zones using high resolution colour displays. *Ophthalmic and Physiological Optics* 1992;12:133-136.
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