The role of lightness in color discrimination among adults with autism

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ABSTRACT

There is a growing body of evidence that Autism Spectrum Disorder (ASD) entails diverse vision alterations, which, in turn, may lead to many behavioral symptoms of ASD. A handful of studies have focused on color vision, reporting unanimously atypical color discrimination in ASD. Despite its importance in visual perception, very little is known about the role of *lightness* in color vision in ASD. This study aimed to examine whether color discrimination in varying lightness is atypical among adults with ASD. A computer program with three test blocks differing in types of stimuli was specifically developed for carrying out this study. 15 adults with Asperger syndrome (AS) and 15 typically developing adults (TD) participated. Three of the participants in the former group were also diagnosed with ADHD. This study found (1) that the AS group performed as well as the TD group in most tested color categories; (2) several differences were found in the red color category in the AS group related to age; and (3) individuals with ADHD outperformed the others in the AS group in the blue color category. However, the analysis also showed a lack of consistency across the different types of stimuli and color categories. This thesis concludes with insights gained from the analysis which can be used to shed further light on the role of lightness in color perception in ASD.

Keywords: Asperger syndrome · High functioning autism · Color vision · lightness · Adult

1. INTRODUCTION

Autism Spectrum Disorders (ASDs) are neurodevelopmental disorders that are characterized by impairments in social/interpersonal interaction, and restricted behaviors (American Psychiatric Association, 2013). In addition to behavioral symptoms, there is a body of studies that suggest a high prevalence of altered sensory processing across multiple modalities in ASD, i.e., vision, hearing, olfaction, tactile sensation, as well as the multisensory integration of these (reviewed by Thye et al., 2018). The gravity of the perceptual symptoms is correlated with the severity of ASD symptoms and, as a consequence, the level of social functions (Kern et al., 2007). Vision, the core sense in detecting social cues, has also been frequently studied in order to better understand ASD. In addition to hypo- and hypersensitivity to certain visual stimuli, gaze atypicalities such as gaze avoidance, impaired gaze following, and joint attention were also reported as common ASD symptoms (Nyström et al., 2017). To explain those visual symptoms, studies were conducted in various areas related to vision, revealing visual alterations such as optometric issues, visual acuity, spatial vision, gaze detection, contrast sensitivity, depth and motion perception in varying types of stimuli (reviewed by Simmons et al., 2009).

As the field of vision in ASD gains more scientific attention, some researchers have started paying attention to *color vision* in ASD. A handful of studies were made so far within the subject, mainly focusing on the following issues: color preference among children with ASD, its role in therapeutic interventions, and color discrimination. Strong affinities or aversion to objects with specific colors among children with ASD has been frequently reported by anecdotal evidence from caregivers, clinicians and through case studies (Ludlow et al., 2014). A recent study examined the preferences of autistic and typically developing (TD) children among six colors, red, pink, yellow, brown, green, and blue, in a clinical setting. They found the ASD group to have a significant preference for green and brown, and an aversion to yellow compared to the TD group (Grandgeorge & Masataka, 2016).

Other studies focused on the therapeutic benefits of colors, especially reduction in visual stress and enhancement in performance among individuals with ASD. In a study of judging emotional intensity among schoolchildren with ASD, self-chosen preferred color tint enhanced performance significantly, which was not observed in the TD group (Whitaker et al. 2016). A similar effect was also observed in other studies focusing on reading speed and detecting changes in visual stimuli in pictures of everyday objects. Children with both high- and low-functioning autism showed a significant improvement in performance in both subtests (Ludlow, Willins, & Heaton, 2006; Ludlow et al., 2008).

Four studies so far have focused on more direct investigations of color discrimination in ASD. Heaton et al. (2008) asked children with low-functioning autism to point to the most different color among three color patches. The autism group showed significantly poorer performance compared to the TD group. Franklin et al. (2008) questioned the test group's cognitive ability and lack of a control task in the study by Heaton et al. (2008). They replicated the former experiment with control stimuli consisting of forms (rather than colors), which led to a result consistent with that of Heaton et al. (2008), that is, children with autism showed significantly lower accuracy for stimuli in all three colors, red, green and yellow. The same study also revealed that children with autism were less accurate in detecting color stimuli with a chromatic background in the same color category. However, when the background color was from another color category, it did not affect their performance (Franklin et al., 2008).

Later, Franklin et al. (2010) performed a more extensive investigation of color discrimination with an ASD group to seek more powerful evidence for the reduction in chromatic discrimination and to quantify this reduction. First, they use a standardized measure of chromatic discrimination, the Farnsworth-Munsell 100 hue test (Farnsworth, 1943), where participants were asked to line up colored plastic caps in order of hue, with only the first and last cap of the hue series in position. Children with High-Functioning Autism (HFA) made more errors in the test than the TD group regardless of the color axis (red-green and blue-yellow axes). To rule out concerns about task difficulty, and to quantify the chromatic sensitivity with more precision, Franklin et al. (2010) also administered a computer test with the Zest algorithm (Zippy Estimate of Sequential testing) that decides task difficulty depending on the respondent's previous responses in order to reach the preset error rate of 18%. The program computed the just-noticeable-difference (jnd) threshold of the respondents' chromatic discrimination ability. A chromatic circle consisting of two halves of different chromaticities was presented and children with HFA and TD responded if the color-defined boundary line was sloping left or right. This test also confirmed their prior study, as well as the results obtained by Heaton et al. (2008), namely, that children with ASD have a reduced chromatic discrimination ability.

A recent study on color discrimination in ASD (Zachi et al., 2017) administered a computer-based test, called the Cambridge Color Test (CCT), which determines color vision deficiencies related to L-, M- and S-cones in the eye. Three groups of children were tested; high-functioning autism (HFA), Asperger syndrome (AS) and typically developing children (TD). Elevated color discrimination thresholds were found both in the HFA and AS groups, that is, those groups had more difficulties in discriminating colors. The result reinforced previous findings obtained by other methods, namely, that color discrimination may be poorer in ASDs (Ludlow et al., 2006; Franklin et al., 2008, 2010; Heaton et al., 2008).

Despite the brief history of color vision studies, achieved results from the four studies mentioned above provide strong evidence of reduced color sensitivity in ASDs. A common feature of all the studies in this subject is that they focused on materials varying in chromaticity. Luminance, one of the key elements of color along with hue, has been seldom studied in ASD research. To the best of my knowledge, only one study about the effect of luminance on chromatic discrimination has been reported in the literature (Franklin et al., 2010). In this study, luminance was used in a control task for the main chromatic discrimination threshold test. This control test was used to assess the task difficulty of the study's main test, which focused on chromaticity. The result showed that there was no significant difference in luminance discrimination in chromatic samples.

Luminance is a frequently used concept in light perception in human vision. This is a unit of light intensity measured by color analyzers and luminance meters (in cd/m^2, candelas per square meter), with a linear relation between light input and output. Luminance is known to play a significant role in human visual perception (Clery, 2013). Luminance in combination with chromatic information specifies the shape and shading of an object. Even a natural object of a uniform color can show variations in luminance across its surface, hence luminance also gives information about the material and pattern of the object (ibid). Luminance-defined contours assist in experiencing dimensions, object boundaries and perceptual organization of the visual scene (Khuu et al., 2016). Furthermore, the contrast in luminance gives cues about aerial depth perception; objects at a great distance have lower color saturation and lower luminance contrast.

Color is commonly represented in any of several color models. One such model is the Hue-Saturation-Lightness (HSL) model. This color model was introduced in the 1970s to align computer graphics with human vision. A specific color is thus defined as an HSL triple (h,s,l) where h is a rotation between 0 and 360 degrees around a color cylinder, s is a percentage of saturation, and l is a percentage of lightness. Although the lightness component of a color defined as an HSL triple does not capture exactly the perceived luminance of the color, varying l allows to lighten or darken a color of a given hue and saturation. Moreover, this relation is monotonic, that is, an increase in lightness will lead to an increase in luminance (albeit in a non-linear fashion). The HSL color model also has the property that *l*=0% is pure black, and *l*=100% is pure white.

Despite the scarcity of studies on the direct effect of luminance/lightness in visual perception among ASD, many studies have noted the prevalence of high light sensitivity in this group (Bogdashina, 2003). Hyper-sensitive individuals presented aversion to dark and bright lights and demonstrated to dislike sharp flashes or lights by covering their eyes. Hypo-sensitive ASD individuals showed attraction to light and light reflections. Studies on sensitivity to the different types of light and autism have a long history (Colman et al., 1976; O'Leary et al, 1978). Individuals with autism were more sensitive to fluorescent lighting than to incandescent lighting, where the former aggravates visual symptoms. Another explanation in hyper/hypo light sensitivity in ASD is an abnormality in pupillary light reflex (PLR). Studies show that dysregulation in PLR in ASD is observed even very early in life. Enhanced PLR among infants is associated with an autism diagnosis in toddlerhood (Nyström et al., 2018), and higher prevalence in abnormal PLR in ASD was noted throughout childhood (Fan et al., 2009; Daluwatte et al., 2015; Dinalankara et al., 2017).

There has not been any direct investigation of the role of luminance/lightness in color perception in ASD so far. However, two studies in ASD, whose primary aim was not about color vision, may indicate abnormal lightness perception in color discrimination among ASD individuals. In a study on the perception of cast shadows, children with high functioning autism perceived shadows abnormally compared to a typically developing control group (Becchio et al., 2010). In identifying the object in pictures, lightness-defined shadows in chromatic objects interfered rather than helped the task of object recognition. In a study of dimensionality perception with adolescents with ASD, the ASD group made a significantly greater number of errors in drawing a green colored object when the contours were defined by lightness, and not with black lines (Sheppard et al. 2009).

The analysis of previous research related to color vision in ASD presented above leads to the following insights: (1) a small but consistent body of work gives evidence of the fact that color discrimination in ASD is atypical; (2) the literature in this field is limited to studies involving children; (3) visual symptoms that may be caused by abnormal light perception are prevalent in ASD; (4) no study has explicitly focused on the role of luminance/lightness in color discrimination in ASD, neither among children, nor adults.

This thesis proposes an initial study aimed at assessing the role of luminance/lightness in color discrimination. The primary research question addressed in this thesis is the following: does lightness discrimination capability differ in ASD as compared to TD counterparts? Considering the prior studies mentioned above, we hypothesize that the ability to discriminate colors differing in lightness is hampered among individuals with ASD. Our research question is operationalized by dividing it into three specific questions, each of which is assessed via the use of a test. The specific questions are:

1. Does the finest threshold in lightness discrimination differ between these two groups?
2. Does the presence of multiple stimuli varying in lightness affect lightness discrimination ability?
3. Is discrimination ability affected by motion in the stimuli?

Reflecting the main hypothesis, we expect an affirmative answer to these three specific questions. A computer program with three test blocks differing in types of stimuli was developed accordingly. The first block (addressing question 1) consisted of static stimuli for measuring the lightness discrimination threshold; the second block (addressing question 2) consisted of static stimuli for measuring the interference effect; the third block (addressing question 3) consisted of dynamic stimuli for measuring cardinal motion detection. The test was administered to both an ASD and a typically developing group (TD). Like prior color vision studies, we administered a range of colors to see if any atypicality was restricted to a specific color category. Also, reaction time to every single stimulus was recorded as a dependent variable for further between-group comparisons.

2. METHOD

2.1. Participants

Totally, thirty adults participated in this study. Five females and ten males with autism were recruited from the Adult Habilitation Center in Örebro Municipality, Sweden. All individuals had been diagnosed with Asperger syndrome (AS) according to the Diagnostic and Statistical Manual of Mental Disorders IV (DSM-IV, American Psychiatric Association, 1994) criteria by trained clinical psychologists and psychiatrists prior to the test. Three of these individuals had also been diagnosed with ADHD. All had graduated Swedish communal high school, and two had a bachelor's degree. Fifteen typically developing (TD) adults, matched for gender, age, and educational background, were recruited through advertisements posted at Örebro University and on social media. Individuals in the TD group had no neuropsychiatric diagnosis. All participants gave written, informed consent before participating. This study was approved by the Ethics Committee of the Institute of Psychology of Örebro University. All data resulting from the study was stored anonymously. Table 1 summarizes the characteristics of the two groups.

Table 1. *Characteristics of the AS and TD group.*

	AS		TD	
	Female	Male	Female	Male
N	5	10	5	10
Age	28.8	36.5	29	36.8

	(Range 22-45, SD 9.2)	(Range 22-52, SD 8.8)	(Range 22-43, SD 9.6)	(Range 23-54, SD 9.8)
Age, diagnosed	28.4 (Range 13-52, SD 11.8)	21.4 (Range 10-32, SD 8.7)	-	-
ADHD (N)	2	1	-	-

It is worth noting that AS was included in the DSM-IV and in the current edition of the International Statistical Classification of Diseases and Related Health Problems (ICD, World Health Organization, 1994). In the DSM-V, however, the term AS has been removed. Since the DSM-V does not provide a strict enough category to describe this group, researchers commonly adopt the term High Functioning Autism (HFA) to refer to this group. Both HFA and AS are a mild form of ASD without intellectual disability. However, the difference between AS and HFA has been controversial among researchers. Current studies show evidence of a such a difference, based on IQ profiles (reviewed by Chiang et al., 2014), emotional recognition (Montgomery et al., 2016), and lexical processing (Speirs et al., 2011). Consequently, this thesis adopts the term AS, refraining from the less understood term HFA.

2.2. Apparatus, stimuli, and procedure

Apparatus. The test was implemented as a Javascript application, and could, therefore, be carried out entirely via a web browser. All tests were displayed in full-screen mode (no other stimuli were present on the screen except for those inherent to the test). The same laptop computer was used for all participants, namely, a Lenovo ThinkPad W550s with a 15.6-inch screen displaying at a resolution of 28801620 pixels with a refresh rate of 60 Hz (CIE 1931, $x_{red} = 0.6523$, $y_{red} = 0.3291$, $x_{green} = 0.3242$, $y_{green} = 0.5996$, $x_{blue} = 0.1504$, $y_{blue} = 0.0449$). The laptop was brought to an indoor location that was convenient for each participant, and efforts were made to ensure even and dim lighting, comfortable sitting position, and absence of other disturbances. The luminosity of the screen was always set to maximum. Participants were asked to sit 50 cm away from and at eye-level to the monitor. A mouse was provided and placed appropriately according to each participant's dominant hand.

Stimuli. The entire test battery consisted of three groups of tests. In each group, the stimuli were presented in six different colors. Primary and secondary colors in the additive color system were used, namely: red, green, blue, yellow, cyan and magenta. The specific color definitions used are shown in Table 2.

Table 2. *Definition of base colors used in the stimuli*

		HSL color space (h,s,l)		
Color	Hex value	h	s	l
Red	#FF0000	0°	100%	50%
Green	#00FF00	120°	100%	50%
Blue	#0000FF	240°	100%	50%
Yellow	#FFFF00	60°	100%	50%
Cyan	#00FFFF	180°	100%	50%
Magenta	#FF00FF	300°	100%	50%

The HSL color space was used to produce variations in these base colors for the purpose of defining the stimuli, as shown below. HSL is an alternative representation of the RGB color model that has been designed specifically for computer graphics to more closely reflect human color perception and resembles the Munsell color model often used in color perception studies (Franklin et al., 2010). HSL allows varying luminosity while maintaining quasi-constant chromaticity. Specifically, hue and saturation characterise the chromaticity of the color: hue is a degree on the color wheel from 0° to 360°, where 0° is red, 120° is green, and 240° is blue; saturation is a percentage value, where 0% means a shade of gray and 100%

is the full color. The remaining dimension, lightness, is also a percentage: 0% is black, 100% is white, and any percentage in between is a shade of the color defined by the hue-saturation pair. The HSL color space is a relative color space, that is, it is a transformation of the RGB color space. As a consequence, the lightness dimension does not have a linear relation to actual perceptual luminance. It has been noted, for instance, that varying saturation may also lead to variation in lightness, and that colors designated as having the same lightness may differ in perceived luminance (Brewer, 1999). The HSL color space was chosen despite these drawbacks due to its ease of use, and the lack of appropriate color calibration tools. Also, it was deemed sufficient for this study that variations in perceived luminance were achieved, and the issue of ensuring equal variation with different chromaticities was deemed of secondary importance.

Block 1: Single static stimuli. This test block aims to estimate the lightness discrimination threshold in the six different color groups. On a fixed background with constant hue and saturation, participants discerned a circle varying in lightness. The lightness of the circle was varied along a scale of thirteen constant deviations from the lightness of the background (Δl =0.01, minimum/maximum value of l = -0.06/0.06) The order of presentation of the tests in the block was randomized, and the same order was maintained for all participants. Participants were asked to input whether the circle was discernible (“Ser du cirkeln?”). The answer was given by clicking on “Ja” or “Nej”. Two examples are shown in Figure 1.

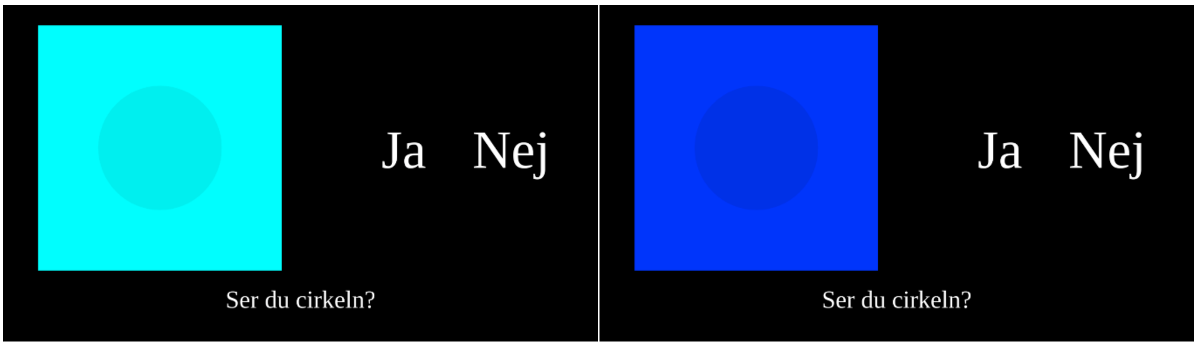

Figure 1. *Example stimuli in block 1.*

Block 2: Multiple static stimuli. This test block aims to see if the presence of other stimuli in similar lightness affects color matching. Multiple stimuli were presented. First, for each of the six reference colors, the reference color was shown beside a pallet of four colors differing from the reference color in lightness. One of the four tiles was always of the same color as the reference color ($\Delta l_0 = 0$), while the other three differed in lightness by the following amounts: $\Delta l_1 = 0.3, \Delta l_2 = 0.4, \Delta l_3 = 0.6$. The placement of the four tiles was randomized but remained the same for all participants. Participants were asked to select the color patch that matched the reference color by clicking on it ("Hitta samma färg"). The same test was repeated with nine color tiles, varying in lightness by the amounts: $\Delta l_1 = 0.3, \Delta l_2 = 0.35, \Delta l_3 = 0.4, \Delta l_4 = 0.45, \Delta l_5 = 0.6, \Delta l_6 = 0.65, \Delta l_7 = 0.7, \Delta l_8 = 0.75$.
Examples of these stimuli are shown in Figure 2.

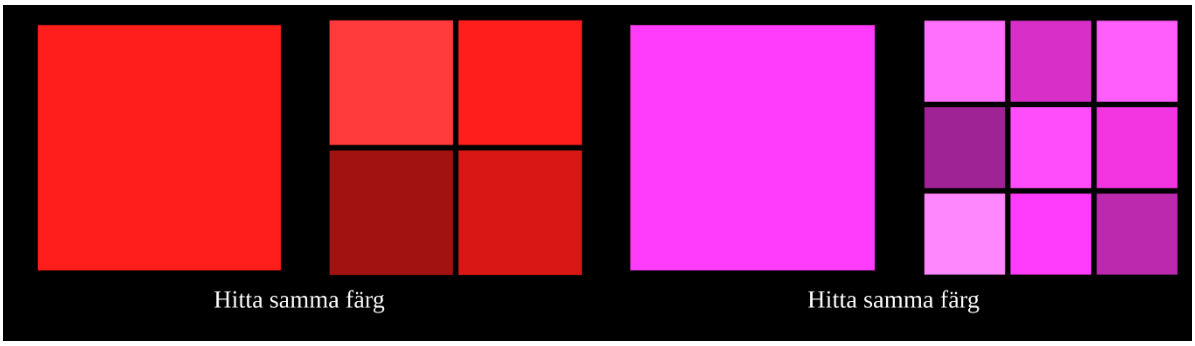

Figure 2. *Example stimuli in block 2.*

Block 3: Dynamic stimuli, cardinal motion detection. This test block aims to measure the ability to detect motion determined by variation in lightness. A lightness-defined line moving in one of four cardinal directions was shown for each of the six reference colors, and participants were asked to identify the direction of motion ("Åt vilket håll rör sig linjen?"). Specifically, in each stimulus, a tile with a continuous gradient (fixed hue and saturation, varying lightness) ranging in the interval [0.4,0.6] was shown. The gradient advanced at a speed of 10.22 pixels per second in one of the cardinal directions (up, down, left, right). The test was repeated with lightness interval [0.45,0.55]. Examples of the stimuli are shown in Figure 3.

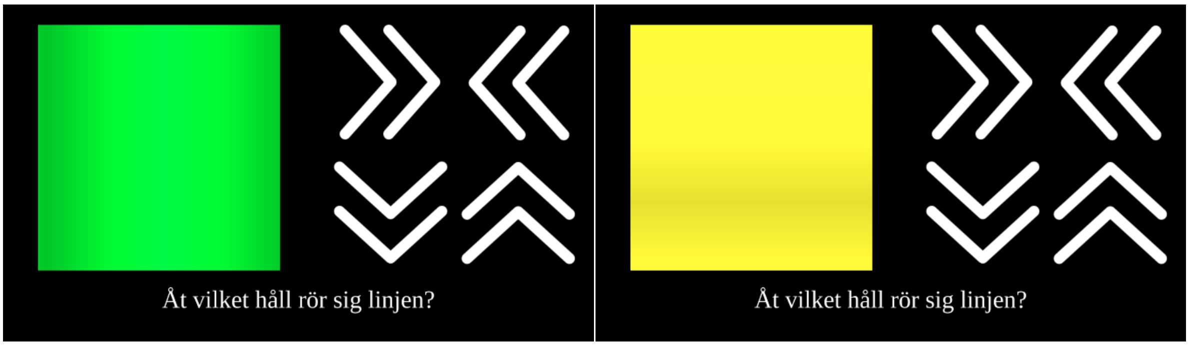

Figure 3. *Example stimuli in block 3.*

Procedure and controls. All participants had normal or corrected-to-normal vision (with and without glasses). Before participating in the test, participants completed the Ishihara color vision test (Ishihara, 1987) to exclude color-blindness (none were excluded). Participants were also subjected to color category discrimination screening. For this purpose, the six reference colors were used, and participants were asked to match each of the reference colors among a pool of samples (no participants failed this screening either). Participants were tested individually in a dimly lit room in presence of the instructor. Procedural instructions were given verbally to each participant prior to each test block. A sample test with significantly larger lightness variation followed thereafter to provide an opportunity to practice. When participants understood the instructions fully and successfully completed the sample tests, the actual test was initiated. Participants were instructed to respond to each stimulus as soon as possible, without "thinking about it too much". No feedback was given to the participants about their answers during and after the test, neither verbally by the experimenter, nor by the test program.

3. RESULT

3.1. Analytic plan

This study initially aimed to measure the differences in color lightness perception between the AS and TD groups. The range of skewness and kurtosis and the result of the Shapiro-Wilk's test showed that assumptions of normality were not met in this data. Therefore, this analysis was performed with the Mann-Whitney U test, a non-parametric test for two independent groups. Constraints on recruiting led to groups that were more heterogeneous than is praxis in ASD studies. Specifically, age varied between 22 and 54 and most participants got their diagnoses in their adult age (age of diagnosis range: 10 to 52). Spearman's rank correlation tests were performed in each block to assess whether there was any correlation between the outcomes and the age at which AS participants were diagnosed, as well as their current age.

It is known that individuals with ADHD have difficulties in color discrimination in the blue-yellow color spectrum (Banaschewski et al., 2006; Tannock et al., 2006). In this study, three participants in the AS group also had an ADHD diagnosis. Due to the small sample size, however, we did not perform further significance tests, rather we present additional descriptive statistics of the results considering the three ADHD participants as a separate group.

3.2. Result

Block 1: Single static stimuli

An collection of descriptive statistics regarding the performance of participants in the three blocks of tests is shown in Table 3.

Table 3. *Descriptive statistics for n_e, Δl_{max} and t_r between AS and TD in block 1*

	AS			TD		
	M	SD	Mdn	M	SD	Mdn
	n_e					
Red	6.00	1.732	6.00	4.93	1.223	5.00
Green	4.87	.640	5.00	4.73	.704	5.00

Blue	2.67	2.059	3.00	1.93	.704	2.00
Yellow	5.20	.775	5.00	4.60	.737	4.00
Cyan	5.87	.352	6.00	5.87	.516	6.00
Magenta	3.93	1.100	4.00	3.60	1.183	3.00
	Δl_{max}					
Red	.037	.008	.040	.032	.004	.030
Green	.060	.000	.060	.060	.000	.060
Blue	.031	.022	.030	.021	.008	.020
Yellow	.052	.008	.050	.047	.008	.050
Cyan	.058	.004	.060	.060	.000	.060
Magenta	.033	.007	.030	.034	.011	.030
	t_r (ms)					
Red	1671	423	1642	1462	433	1278
Green	1433	494	1274	1417	421	1270
Blue	1677	555	1392	1458	288	1378
Yellow	1372	396	1248	1348	365	1310
Cyan	1307	302	1192	1396	315	1382
Magenta	1507	507	1392	1359	403	1235

A Mann-Whitney U test with AS and TD groups was conducted in each color category on (1) number of errors n_e, (2) maximum difference between lightness of the chosen color and of the reference color Δl_{max}, and (3) reaction time t_r. No significant difference between groups was found in all three variables throughout the six color categories, with one exception: the AS group made more errors (higher n_e) in the red color category than the TD group, U=60.5, p=.027 (2-tailed, Mdn= 6 in AS, Mdn=5 in TD). However, still in the red category, Δl_{max} and t_r were not significantly different between the two groups.

No correlation was found between the three variables and the age at which AS participants were diagnosed, nor their current age, except for t_r in the red color. There was a moderate, positive monotonic correlation between current age and t_r in the AS group, that is, the older the participant, the slower their reaction time (r_s=.59, n=15, p=0.02). This was not observed in the TD group.

It is known that individuals with ADHD have difficulties in color discrimination in the blue-yellow color spectrum (Banaschewski et al., 2006; Tannock et al., 2006). In this study, there are three participants in the AS group that were also diagnosed with ADHD. This group outperformed not only the other participants in the AS group, but also those in the TD group in n_e and Δl_{max} in the blue color category (see Table 4). Note that the previous Mann-Whitney U test did not reveal any difference in n_e and Δl_{max} between the AS and TD groups in the blue color category. This is ascribable to the three individuals in the AS group with ADHD. Another Mann-Whitney U test was carried out on the AS and TD groups without those three individuals with ADHD. In Δl_{max}, the AS and TD group showed a significant difference, U=44, p=.022 (2-tailed, Mdn= .040 in AS without ADHD, Mdn=.020 in TD). In n_e, the difference was still not significant U=52, p=.054 (2-tailed, Mdn=3 in Only AS, 2 in TD and 1 in both AS and ADHD), however bigger than when the ADHD participants were considered in this group. Similar observations were not made in any other color categories, including yellow, which is the other known "problem color" for individuals with ADHD (see Table 4). Since the size of the ADHD group is very small (n=3), we limit ourselves to this descriptive analysis, deferring a more extensive study on this issue to future work.

Table 4. *Performance descriptions in blue and yellow color categories in block 1, considering ADHD as a separate group.*

		Both AS and ADHD (n=3)		Only AS (n=12)		TD (n=15)	
		M	SD	M	SD	M	SD
Blue	n_e	.67	.577	3.17	1.992	1.93	.704
	Δl_{max}	.007	.006	.038	.020	.021	.008

	t_r (ms)	1656	236	1682	618	1458	288
Yellow	n_e	5.33	.577	5.17	.835	4.60	.737
	Δl_{max}	.053	.006	.060	.000	.047	.008
	t_r (ms)	1266	176	1399	436	1348	365

Block 2: Multiple static stimuli

Another Mann-Whitney U test was conducted on Δl_{max} and t_r in each color category, with both 4 and 9 color tiles. No significant difference was found in both variables between AS and TD throughout the six color categories, except for the significantly delayed reaction time t_r in the AS group in the blue color category with four samples, U=43, p=.003 (2-tailed, Mdn=3623 in AS, Mdn=2479 in TD). However, this was not observed in the test with nine color tiles in the same color category, U=98, p=p.283 (Mnd=4719 in AS, 4450 in TD). For descriptive information in all the color categories, see Table 5.

Table 5. *Descriptive statistics for Δl_{max} and t_r between AS and TD groups in block 2.*

	AS			TD		
	M	SD	Mdn	M	SD	Mdn
Δl_{max} in 4 tiles						
Red	.020	.041	0	.007	.026	0
Green	.033	.049	0	.053	.052	.10
Blue	.013	.035	0	.000	.000	0
Yellow	.013	.035	0	.007	.026	0
Cyan	.053	.052	.10	.027	.046	0
Magenta	.027	.046	0	.013	.035	0
t_r in 4 tiles (ms)						
Red	3532	1641	3118	2982	1063	2685
Green	4461	2759	3510	2921	1188	2800
Blue	3954	1499	3623	2551	510	2479
Yellow	3064	1242	2751	2769	952	2423
Cyan	4317	2421	3608	3545	1720	2952

Magenta	3997	1476	3440	3391	1090	3165
Δl_{max} in 9 tiles						
Red	.017	.031	0	.040	.034	.05
Green	.057	.053	.05	.033	.041	0
Blue	.023	.037	0	.030	.041	0
Yellow	.017	.036	0	.017	.041	0
Cyan	.123	.088	.15	.133	.088	.15
Magenta	.041	.057	.01	.047	.061	.05
t_r in 9 tiles (ms)						
Red	6241	6387	4565	4142	2040	3597
Green	5353	2582	4517	4426	3002	3599
Blue	6118	4959	4719	4746	2195	4450
Yellow	3886	1294	3663	3824	2052	3434
Cyan	5013	2430	4984	5156	2875	3718
Magenta	4962	2475	3997	4297	2129	3628

Another Spearman's correlation test found no correlation except for Δl_{max} in the red color category with four tiles. There was a moderate, positive monotonic correlation between diagnosed age and Δl_{max} in the AS group, that is, the older the age of diagnosis, the larger the error (r_s=.542, n=15, p=0.037). This was not observed in the TD group. The current age, on the other hand, showed no correlation.

As done in block 1, we investigated the role of ADHD in the blue and yellow color categories, see Table 6 for descriptive statistics. As shown, the ADHD individuals showed a similar pattern as in block 1, outperforming in the blue color category the others in the AS group. This was observed in the nine-tile test, but not in the smaller test with four tiles.

Table 6. *Performance descriptions in blue and yellow color categories in block 2, considering ADHD as a separate group.*

	Both AS and ADHD (n=3)	Only AS (n=12)	TD (n=15)

		M	SD	M	SD	M	SD
Four tiles							
Blue	Δl_{max}	.000	.000	.017	.039	.000	0
	t_r (ms)	3868	1094	3976	1625	2551	510
Yellow	Δl_{max}	.033	.058	.008	.029	.017	.041
	t_r (ms)	2727	528	3148	1369	2769	952
Nine tiles							
Blue	Δl_{max}	.017	.029	.025	.040	.030	.041
	t_r (ms)	4958	2454	6408	5453	4746	2195
Yellow	Δl_{max}	.000	.000	.021	.040	.017	.041
	t_r (ms)	4969	2152	3616	942	3824	2052

Block 3: Dynamic stimuli, cardinal motion detection

All participants identified the cardinal directions correctly in all color categories. A Mann-Whitney U test was conducted on only t_r in each color category. See Table 7 for descriptive statistics of the result. The result showed that the AS group had significantly slower t_r with gradient width [0.4,0.6] in the blue, red and magenta color categories compared to the TD group; blue U=61, p=.033 (Mnd=3039,00 in AS, 2460,00 in TD), red U=34, p=,001 (Mnd=3168,00 in AS, 2258,00 in TD), magenta U=54.5, p=,016 (Mnd=2449,00 in AS, 2123,00 in TD). No significant difference was found in the other color categories. No significant difference was found in any color category when the gradient width was decreased to [0.45,0.55].

Spearman's correlation test showed that there was no correlation with age of diagnosis or current age in both the AS and TD group.

Table 7. *Descriptive statistics for t_r between AS and TD in Block 3*

	AS			TD		
	M	SD	Mdn	M	SD	Mdn
t_r with width [0.4.0.6] in ms						

Red	3227	863	3168	2312	431	2258
Green	2755	893	2476	2399	447	2266
Blue	3335	1197	3039	2415	508	2460
Yellow	2639	820	2437	2526	638	2348
Cyan	2427	653	2289	2449	568	2397
Magenta	2797	870	2449	2115	437	2123
t_r with width [0.45.0.55] in ms						
Red	3302	835	3180	3008	618	2963
Green	3446	952	3514	3039	754	2725
Blue	4261	1634	3939	3363	833	3002
Yellow	3853	1396	3602	3348	489	3212
Cyan	3214	910	3222	2895	677	2869
Magenta	3081	936	2732	2639	514	2587

Again, individuals with both AS and ADHD showed better performance than the rest of the AS group in the blue color category. See Table 8.

Table 8. *Performance descriptions in blue and yellow color categories in block 3, considering ADHD as separate group.*

		Both AS and ADHD (n=3)		Only AS (n=12)		TD (n=15)	
		M	SD	M	SD	M	SD
t_r with width [0.4.0.6] in ms							
Blue	t_r (ms)	2955	875	3430	1279	2415	508
Yellow	t_r (ms)	2420	810	2693	848	2526	638
t_r with width [0.45.0.55] in ms							
Blue	t_r (ms)	3594	1543	4428	1677	3363	833
Yellow	t_r (ms)	3603	1023	3916	1506	3348	489

4. SUMMARY AND DISCUSSION

This study aimed to investigate performance in color lightness discrimination among individuals with and without autism, a previously unexplored topic in the literature. This was the first study in color discrimination in ASD that focused on adults, and the first to focus explicitly on the role of lightness in color discrimination. During the analysis, it was found that individuals with AS performed almost as well as the TD group in our tests. Significant differences were found in a subset of the color categories, however the results lack consistency across the various types of stimuli. Further considerations on this issue are discussed below. Prior research findings showed that individuals with ADHD have difficulties in color discrimination in the blue-yellow color spectrum. This is also discussed below in light of the findings of the present study.

One color that distinguishes the AS group from the TD group repeatedly throughout the three test blocks is *red*. Individuals with AS made more errors (n_e) in the red color category in block 1 (which measures discrimination threshold). In the same block, Spearman's correlation also revealed a moderate, positive correlation between current age and reaction time in the red color in the AS group. Conversely, no age-related effect was visible in the TD group. In block 2, the diagnosed age was moderately correlated with the size of the error (Δl_{max}) in the red color category. In block 3, the AS group showed slower t_r compared to the TD group in the red color category. Reduced chromatic sensitivity in the red color was once reported by Franklin et al. (2010). However, in their luminance task, a control task to the chromatic sensitivity test, they did not find any significant difference between HFA (high functioning autism) and TD groups. Our finding, therefore, contradicts their result. One possible explanation is that the age of the participants in the present study varied widely (AS group: 22-52, TD group: 22-54), contrary to the study of Franklin et al. (2010, age range in both HFA and TD group: 11-14). As implied by the Spearman's correlation test, aging may affect red color perception in the AS group. This phenomenon has not been explored in the literature on color vision in autism, and therefore requires future investigation.

Chromatic sensitivity is known to peak around adolescence and declines thereafter with age (Knoblauch et al., 2001). Contrary to chromatic sensitivity, lightness sensitivity in color contrast does not degrade with aging generally (Fiorentini et al., 1996). The results in this thesis confirm that this applies to adults with ASD as well, except for the red color category as mentioned above.

Although the sample of participants with both ADHD and AS was small (n=3), these individuals showed much smaller lightness discrimination threshold in the blue color category (block 1), that is, they were better at detecting smaller lightness differences in the blue color than all other participants, including the TD group. They also outperformed the rest in the AS group and performed mostly as well as the TD group in the blue color category in blocks 2 and 3. With a sample size of three, it is hard to draw any significant conclusions regarding this observation. However, it is worth noting that previous studies show that individuals with ADHD have more difficulty performing *chromatic discrimination* tests that involve the blue-yellow color axis. Retinal dopamine hypofunction has been pointed to as a possible explanation (Banaschewski et al., 2006). This blue-yellow color vision disturbance is also prominent in other disorders that involve an altered dopaminergic system, such as Tourette's syndrome (Melun et al., 2001), Parkinson's disease (Haug et al., 1995) and Huntington's disease (Büttner et al., 1994). The results obtained in this thesis pertain to *color lightness discrimination* ability. The results found here, if confirmed in further studies with more participants, may indicate that ADHD somehow mitigates the otherwise poorer performance in lightness discrimination the blue color category.

The limitations of this study include the following. First, the test group and control group were not strictly matched on IQ. In ASD studies, IQ is frequently used as a means to screen participants in order to more closely match the test and control groups. Due to the lack of time and qualification of the experimenter in assessing IQ, we recruited individuals already diagnosed with AS by the municipal habilitation center in Örebro, which guaranteed that participants with AS had normal IQ. Educational background between the AS and TD groups was matched to the extent possible. Note that a recent study on chromatic discrimination in ASD (Zachi et al., 2017) found no significant correlation between IQ and color discrimination threshold (estimated IQ range in the study: 80-144, N=56).

The analysis presented above reveals a lack of consistency in the performance of the AS group in the three test blocks (see Section 3). A possible explanation, besides the small sample size, is the unmatched task difficulty between the three test blocks. While the first subtest consisted of a sequence of 13 samples in varying luminance in each color category, the other test blocks contained only two levels of difficulty in each color category, requiring much less time to complete. This was intended to reduce afterimages, but may have led to the inconsistency in colors throughout the subtests.

With difficulties in recruiting test subjects in a limited amount of time, the test was carried out in a total of four different physical locations that were convenient for the subjects. All test rooms were dimly lit, silent and devoid of distracting objects. The lightness levels in the color samples were the same for all participants, with the same preset display calibration for the computer monitor. However, the test environments were illuminated slightly differently, and the tests were not re-calibrated accordingly due to the lack of a luminance calibrator. This may have affected perceived luminance.

Another possible improvement for further implementation of the test can be to adopt an algorithm that estimates just-noticeable-difference (jnd). Such an algorithm would modify task difficulty continuously by reducing or increasing the difference from the reference color based on the accuracy of the participant’s previous responses. This type of method has been used in several colorimetry studies and is known to be as a sensitive and reliable measure of color discrimination threshold (Notman et al., 2008). In the lightness discrimination threshold test (block 1), the discrimination threshold range was predetermined by Δl =0.01, minimum/maximum value = -0.06/0.06, which limited possible exploration of any reduction in ability out of the range. In the yellow color category, for instance, many in both the TD and the AS group made errors of maximum magnitude, indicating that a broader range was needed in this color category.

Despite the limitations mentioned above, this study presents a few notable findings that have not been reported in the research field. We find that further investigations in (1) color lightness perception in the red color in ASD, and (2) the impact of ADHD on ASD in blue color lightness discrimination, are needed. Such studies can help to shed light on the important topic of color vision in ASD.

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