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RESEARCH ARTICLE

Greater effect of contrast polarities on visual acuity measurements using chart with shorter wavelength background

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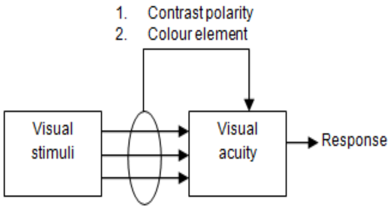
Graphical abstract



Abstract

Our study aimed to explore the effect of positive and negative polarities on visual acuity measurements by utilizing black and white as a text against background with three distinct colours. Visual acuity was recorded as logarithm of minimum angle of resolution (LogMAR) using the detection of the gap in a four-position Landolt-C. The 2x3 (polarity x background color) two way repeated measures ANOVA showed a statistically significant interaction between polarity and colour background on visual resolution [F (2, 16) = 23.704, $p < 0.001$, $\eta^2 = 0.744$]. Among the three primary background colour, shorter-wavelength (blue background) showed statistically significant findings between both positive and negative polarity [F (1, 9) = 39.875, $p < 0.001$, $\eta^2 = 0.818$]. Visual acuity measurements improved with negative polarity but decreased with positive polarity with blue colour background. However, visual acuity was not statistically significantly different with the green (medium-wavelength) [F (1, 11) = 0.625, $p = 0.446$, $\eta^2 = 0.053$] and the red (long-wavelength) backgrounds [F (1, 9) = 4.021, $p = 0.856$, $\eta^2 = 0.000$]. In conclusion, black text against shorter-wavelength (blue) background apparently more difficult to be resolved by human eyes compared with white text. These findings suggest colour element might be an advantage for negative polarity colour combinations.

Keywords: Contrast polarity, contrast ratio, color, visual acuity

INTRODUCTION

Contrast is one of the most important variables for vision performance (Nadler *et al*., 1990). Without sufficient amount of contrast, stimulus for vision might be affected (Hung & Ciuffreda, 2002). Contrast enhances legibility and visibility of objects. Colour is also an important factor in most of the task involved discrimination of details such as in reading (Knoblauch *et al.,* 1991; Legge *et al.,* 1990). A coloured object viewed on a coloured background presents a colour contrast as well as a luminance contrast. They allows human to identify and localize objects that would otherwise be indistinguishable from the background in which they exist, thereby adding greatly to our visual capabilities. Study on the effect of colour on the visual performance during near visual function (reading task) concluded that high contrast was the major determinant factor for maintaining effective reading (Tinker & Paterson, 1931). The finding was further supported in a later investigation (Ling & Schaik 2002). They evaluated the effect of text and background colour on visual search of web pages. Subjectively, it was found that colour combinations with high contrast was favored and resulted in better performance than lower contrast condition. Target constructed in darker text on lighter background or also be called as positive polarity (i.e. black on white) was the preferred choice of print construct given the abundant experience with books, journals, newspapers, printed and display information devices and printed office documents, among other things. Darker target on lighter background provided better conspicuity through improved visual performance by enhancing the legibility and visibility of the target compared to light target on dark background (Buchner & Baumgartner, 2007; Piepenbrock *et al.,* 2013). The effect of colour composition and luminance remained inconclusive with regard to contrast polarity. The effectiveness of colour combination between object and its background was found to be polarity dependent (Humar *et al*., 2008; Humar *et al*., 2014). However, a major problem with most previous experimental design was that the luminance and colour factors were not systematically varied or measured with respects to effects of polarity.

In any environment, contrast was the element to affects visibility of the object. A dark red ball of large round shape was likely to be easily attracted by the attention compared to light red ball of small round shape. By definition, contrast is the manifestation of differences in attributes of virtue object seen simultaneously such as luminance and colour (Millodot, 2009). It is generally accepted that contrast was the evaluation of the detection of objects (Rachel, 2001). Luminance was defined by the total luminous intensity emitted per unit projected area of a source in a given direction (Boyce, 2014). The unit of measurement of luminance was candelas per square metre (cd/m^2). It was being used most commonly in specifying the stimulus for vision. The changes in luminance due to difference between two areas (e.g. between an object and its immediate background) was refer as luminance contrast (Nadler *et al.,* 1990). It calculates the ratio between the two specified areas. The fundamental behind studying contrast was to determine thresholds for given contrast of that particular stimulus (Legge *et al*., 1987). Ability to detect a target from its background or to resolve detail within a target is defined as spatial threshold (Boyce, 2014). Common spatial threshold tests were visual acuity and contrast sensitivity (Ian, 2006; Pelli & Bex, 2013; Woods & Wood, 1995). The main focused in spatial threshold was variations in luminance across space. Threshold luminance contrast was relevant to the detection of targets on a background. This is because targets with a luminance contrast close to or below the threshold value are unlikely to be seen, and targets with a luminance contrast more than twice the threshold value are likely to be seen every time (Boyce, 2014). When the luminance of the surround is very low relative to that of the immediate background, there is an optimum background luminance for visual acuity, above which visual acuity declines (Sheedy *et al*., 1984). In a highly visual society such as ours, high-frequency resolution is critical. Reading road signs, blackboards, computer screens, and books and watching movies and television are all dependent on a high level of contrast.

In a real world, ability to function (vision) in multicontrast environment is important as it affects the quality of life. Contrast is not merely dependent to the differences in luminance between two adjoining areas. There might be other factors that contributed to the contrast parameters. In certain conditions where both luminance and colour were less effective and conspicuous such as when colour discrimination was inhibited in low light environments, contrast polarity might contribute to visual response enhancement. Collectively, contrast polarity is one aspect of reading in evaluation on visual performance that has been studied in some detail (Buchner & Baumgartner, 2007; Piepenbrock *et al*., 2014; Piepenbrock *et al*., 2013). However, previous studies on polarity and contrast only had small sample sizes, so it was difficult to draw definite conclusions (Humar *et al*., 2008, 2014; Westheimer, 2003; Westheimer *et al*., 2003). The demand for the contrast-detecting component of visual acuity has been reported to decrease when the contrast of the visual acuity chart was reversed (i.e. white-on-black) (Westheimer, 2003). The reduction was mainly due to the changes in the contrast of the features which occur in the retina. It has been hypothesised that the resolutions of reversed-contrast polarity charts differed from that of the traditional charts. The effect of contrast polarity on visual acuity has been investigated by comparing the outcomes of the usage of conventional black-on-white charts and reversed-contrast charts (Westheimer, 2003; Westheimer *et al*., 2003). Evidently, the logarithm of the minimum angle of resolution (LogMAR) was significantly smaller for white letters on a dark background (Westheimer, 2003). However, the study had a small sample size (4 subjects) and did not control the learning effect (constant stimuli were used when measuring the visual acuity, so guessing or biases might have led to inaccurate results) (Schwartz, 2010). Reports on polarity were equally inconclusive. Some claimed that negative polarity was preferred for better legibility (Humar *et al*., 2008, 2014), while others believed that contrast polarity did not affect to visual acuity (Wang & Chen, 2000).

To date, the literature on the effects of polarity upon background colour contrast does not have concrete conclusions about how these two factors impact visual performance. Furthermore, most stimuli used in the previous literature are from complex characters and required more arduous cognitive task such as proofreading performance. Hence, the interactions between contrast polarities upon colour elements in visual performance require further investigations. Our study investigated the interaction effects of contrast polarity (positive and negative) upon three distinct colour backgrounds of fixed luminance contrast (blue, green and red) on visual acuity (dependent variable) using LogMAR scores.

EXPERIMENTAL

Visual stimuli

Visual acuity measurements were carried out in a room of dimensions 7.4 m (length) x 3 m (width) x 3 m (height). The measurements were taken for each of the 6 different modifications of the printed Landolt C (Table 1) chart in a 4 metre LogMAR designs. The luminances of the charts were measured by a Konica Minolta Luminance Meter LS110. The averages of three measurements were taken as the contrast values. The luminance contrast definition of Michelson was used to calculate the contrast ratio and this was based on maximum and minimum luminance of the text and the background (Schwartz, 2010). When the luminance of the text was lower than the luminance of the background, the polarity was considered positive; otherwise it was negative (Table 2). A four-orientation Landolt C chart design was introduced to the subjects (Schrauf & Stern, 2001) with an internally illuminated by standardised light-emitting diodes (LED) lamp that known for its lesser flicker (Fang & Liu, 2017; Santos *et al*., 2017) and provided better colour properties (Boyce, 2014). A calibrated Konica Minolta CR410 was used to measure the colour difference between text and background for the colour set of Landolt C. The colours used in the experiments were properly defined (Robertson, 1977). Chromaticity coordinates were used to describe hue and saturation without taken into account the luminance factor. The coordinates of colours (u' and v') (**Table 3)**

in the CIE 1976 chromaticity diagram were calculated from the measured *x* and *y* values (Robertson, 1977).

Table 1 Six combinations of colour used in the Landolt C chart designs

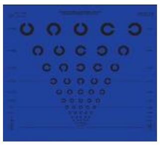
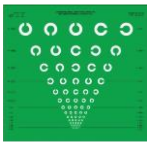
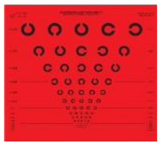
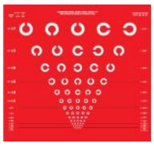
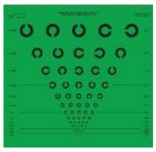
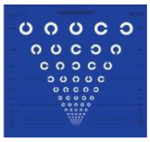
Six combinations of Landolt-C chart designs (Text/Background)	
Positive Polarity	**Negative Polarity**
 P1	 N1
 P2	 N2
 P3	 N3

Table 2 Summary of Luminance Information and Contrast Polarity Classification of the Colour Combination Used in the Four-Position Landolt-C Chart Designs

Six combination of four-position Landolt-C chart designs (Text/Background)	Luminance, *L* (cd/m^2)		Contrast polarity
	Text	**Background**	
Black/Blue	6.76	9.13	Positive

Black/Green	6.76	24.55	Positive
Black/Red	6.76	12.20	Positive
White/Blue	71.47	9.13	Negative
White/Green	71.47	24.55	Negative
White/Red	71.47	12.20	Negative

Table 3 Summary of the CIE Chromaticity Coordinates (*X, Y*) and Uniformity Colour Space Coordinates (*U´, V´)* Information for Five Testing Colours Used in the Study

Coordinate	Colour				
	Black	**White**	**Blue**	**Green**	**Red**
x	0.3057	0.3105	0.2266	0.2657	0.4994
y	0.3191	0.3217	0.2139	0.4483	0.3290
u´	0.197	0.199	0.177	0.136	0.335
v´	0.464	0.464	0.376	0.518	0.497

Procedure

The subjects were seated on an adjustable ergonomic chair, with the Landolt C chart positioned 4 m directly ahead. Six Landolt C charts of different designs were presented to the subjects at random. The subjects were light-adapted for two minutes in the same experimentation room to allow the regeneration of sufficient cone pigments to detect the luminance of the charts (Rachel, 2001). Hence, it was important to ensure that the photoreceptors remained sensitive to the luminance of the charts before the visual acuity measurements were taken. A forced-choice 'criterion-free' method was employed, so that the results were not affected by the cautiousness of the subjects' responses. The visual acuities were measured in terms of the logarithm of the minimum angle of resolution (LogMAR) at which the gap orientations of the Landolt C chart were accurately identified. The scoring was based on the letter-by-letter termination rule, for which the subjects were encouraged to complete a particular line. Scoring acuity letter-by-letter, in which equal credit is given for each correct letter read, produced better test-retest variability and finer grading scale
(Bailey *et al*., 1991). The visual acuities of the subjects were determined binocularly.

Participants

Our study adhered to the tenets of Declaration of Helsinki and was approved by the Research Ethic Committee of the University. Given a total sample size of n = 31 and assuming $\alpha = 0.05$, population effects of size $f = 0.80$ (large effects as defined by Sawilowsky 2009) could be detected for the independent variables with a probability of $1 - \beta = 0.95$. All power calculations were conducted using the GPower analysis program (Erdfelder et al., 1996). Thirty-one subjects of young adults (mean age of 22.46 years ± 1.85) with no known ocular pathology were recruited. All participants were screened with D-15 colour vision test to rule any known colour deficiencies. In this experiment, a single subject repeated the same procedure for several trials. A simple randomization was used to reduce learning effect due to repetitive measurements (Suresh, 2011). The technique maintained complete randomness of the assignment of a target or stimulus presented. The random numbers were generated by using the RANDBETWEEN function in the excel spread sheet.

RESULTS AND DISCUSSION

Interaction between positive and negative text polarity on 3 primary colour background

The data was analyzed using SPSS Statistic Software version 20. Current investigation utilized within-subject study design, where repeated measures of the same subject were performed. Contrast polarity (positive and negative) and colour background (short, medium and long wavelength) were investigated with visual acuity. The dependent measures were analyzed using 2 x 3 (polarity x colour background) two-way repeated measures of analysis of variance (ANOVA). The significant value was set at 0.05. The two-way repeated measures ANOVA was run to determine the effect of positive and negative polarity over 3 complementary colour backgrounds on visual acuity. Analysis of the studentized residuals showed that there was normality, as assessed by the Shapiro-Wilk test of normality and no outliers, as assessed by no studentized residuals greater than ± 3 standard deviations. There was sphericity for the interaction term, as assessed by Mauchly's test of sphericity ($p > 0.05$).

The 2 x 3 two way repeated measures ANOVA showed a statistically significant interaction between polarity and colour background on visual acuity [$F(2, 16) = 23.704$, $p < 0.001$, $\eta^2 = 0.744$]. Post hoc with a Bonferroni correction for multiple comparisons revealed that the visual acuity was statistically significantly reduced in the positive polarity (M = 0.43 LogMAR, SD = 0.05) compared to the negative polarity (M = 0.16 LogMAR, SD = 0.07) on the blue (short-wavelength) colour background [$F(1, 9) = 39.875$, $p < 0.001$, $\eta^2 = 0.818$]. However, visual acuity was not statistically significantly different with the green (medium-wavelength) [$F(1, 11) = 0.625$, $p = 0.446$, $\eta^2 = 0.053$] and the red (long-wavelength) [$F(1, 9) = 4.021$, $p = 0.856$, $\eta^2 = 0.000$].

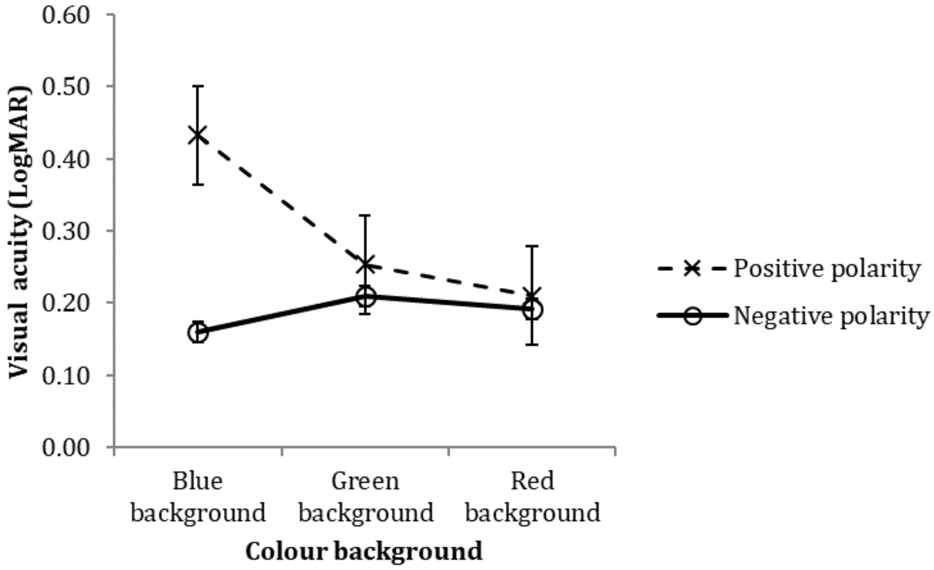


Fig. 1 Mean visual acuity (LogMAR scores) was plotted against colour background in the comparison between positive polarity and negative polarity. The error bars represent the standard errors of the means.

Discussion

Our study revealed that visual acuity measurements improved with negative polarity but decreased with positive polarity with blue colour as background. Black text against shorter-wavelength (blue) background apparently more difficult to be resolved by human eyes compared with white text. In conclusion, colour element might be an advantage for negative polarity colour combinations. Our findings were in agreement with previous studies reported that the minimum angle of resolution was found to be significantly better for negative polarity than for positive polarity (Westheimer, 2003; Westheimer *et al*., 2003). The effect of negative polarity by utilizing white text against different colour backgrounds on visual acuity across the wavelength somehow displayed a similar finding of improvement in LogMAR score than the positive polarity. The same colour difference between text and background was being applied in black Landolt C, but the resolution measurements reduced. Our findings suggested that white text improved colour discrimination when being used against coloured background. This representation was likely to be mediated by luminance factor of the text being used. One possible explanation might be due to the higher luminance value of white text compared to black text. The higher luminance associated with lighter target resulted in more pupillary contraction, which led to a higher-quality retinal image by reducing the effects of spherical aberrations (Lombardo & Lombardo, 2010) and by increasing the depth of field (Green *et al*., 1980), thus reducing the focusing effort and hence improving the quality of the retinal image. When the same subjects were tested on a positive polarity chart, the visual acuity was poorer as compared to the negative polarity. The visual acuity of black text against colour background was found reduced across the colour wavelength from short-wavelength to long-wavelength. Hence it affected the legibility and visibility of the letter seen. Among the three primary colour background, shorter-wavelength (blue colour background) showed statistically significant findings between both positive and negative polarity. Visual acuity measurements upon the blue colour background improved with negative polarity but decreased with positive polarity. Contrast polarity changes affected the resolution measurements of different colour combination chart designs suggests that luminance and colour factors processing occurs independently within systems that were selective for different contrast polarity differences. The observations made in later experiment were likely to reflect the independent process. Previous studies claimed that negative polarity provided better legibility as compared to positive polarity (Humar et al., 2008). However, the black-on-white (positive polarity) and white-on-black (negative polarity) analyses were not conducted in isolation (i.e. without the influence of other colours). Hence, the precise effect of contrast polarity without colour elements on visual acuity was difficult to determine. A similar finding was reported in an investigation which employed 56 colour combinations in a liquid crystal display (LCD) (Humar *et al.,* 2014).

However, the findings of the current study contradict the previous research that has found positive polarity is more advantageous than the negative polarity (Buchner & Baumgartner, 2007; Piepenbrock *et al*., 2014, 2013). The task required in proofreading performance might explain the difference in findings. This suggesting that visual performance in negative contrast polarity is good in the short term but may be reduces in more demanding long term visual conditions. On another note, contrast polarity, be it black-on-white (positive polarity) or white-on-black (negative polarity), in a visual display terminal was reported to have no significant effects on visual performance (Wang & Chen, 2000). The mean visual acuity was not affected by the contrast polarity. The discrepancy might be due to the effect of colour element that was being incorporated in current study design. The earlier investigation was limited to achromatic comparative of target. In addition to that, the psychophysical method used in both studies might contribute to the contradictory results. Our study adopted forced-choice method while the previous study adopted stairacse method. The stairacse method suffered common flaw as other psychophysical method, that is not all observers use the same criteria when deciding whether or not they see a stimulus. There were somehow variations in the observer's threshold criterion. As a solution, forced-choice method was able to minimized the criterion as a confounding factor and hence overcome the problems due to its "criterion-free" method (Treutwein, 1995). That means it helps in producing unbiased observer. This is because observer was encouraged by forcing him or her to choose between several alternative choices without being allowed to guess to give a definite respond (Schwartz, 2010). This could explained the insignificant findings obtained in the earlier study.

There were several limitations in our study. Our sample was young adults (mean age of 22.46 years ± 1.85, n = 31). Therefore, it might not be suitable to generalize the results for pediatric or aging population. The luminance contrast between both polarities were not at fixed value. Hence, it could confounded the findings. However, the main focus was to ascertain the effect between polarity and colour backgrounds. Thus, the inequiluminant of luminance contrast might have least influence to the overall measurements.

CONCLUSION

To summarise, the contrast polarity and colour of the critical detail of the task have a marked influence upon visual acuity that responsible in making sure the objects seen are highly conspicuous and visible. The essence behind this was to ensure those attributes of virtue object strikes visual attention and consequently the visual performance is optimally enhanced in everyday life routine for information retrieval. In conclusion, colour element might be an advantage for negative polarity of colour combinations. However, further investigation is required that cover broader spectrum of wavelength.

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