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After-effects of TFT-LCD display polarity and display colour on the detection of low-contrast objects

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Participants performed a word–non-word discrimination task within a car control display emulated on a thin film transistor liquid-crystal display (TFT-LCD). The task simulated an information read-out from a TFT-LCD-based instrument panel. Subsequently, participants performed a low-contrast object detection task that simulated the detection of objects during night-time driving. In experiment 1, words/non-words were presented black-on-white (positive polarity) or white-on-black (negative polarity). In experiments 2 and 3, display colour was additionally manipulated. A positive polarity advantage in the discrimination task was consistently observed. In contrast, positive displays interfered more than negative displays with subsequent detection. The detrimental after-effect of positive polarity displays was strong with white and blue, reduced with amber and absent with red displays. Subjective measures showed a preference for blue over red, but a slight advantage for amber over blue. Implications for TFT-LCD design are derived from the results.

Statement of Relevance: When using TFT-LCDs as car instrument panels, positive polarity red TFT-LCDs are very likely to lead to good instrument readability while at the same time minimising – relative to other colours – the negative effects of an illuminated display on low-contrast object detection during night-time driving.

Keywords: display colour; display polarity; night-time driving; TFT-LCD

1. Introduction

The presentation of dark letters or symbols on a light background is usually referred to as a positive polarity display, as opposed to negative polarity displays with light letters or symbols on a dark background. The scientific investigation of whether reading from positive or negative polarity displays should be preferred has a long history (for a review, see Pawlak 1986). Several studies have shown that positive polarity text displays on monitors result in better performance than negative polarity displays (Bauer and Cavonius 1980, Radl 1980, Magnussen *et al*. 1992, Hall and Hanna 2004, Chan and Lee 2005, Buchner and Baumgartner 2007). This positive polarity advantage is probably due to the typically higher luminance of positive polarity displays (Buchner *et al*. 2009). Higher luminance results in a reduced pupil size. A reduced pupil size, in turn, implies a greater depth of field and less spherical aberration. Both aspects improve the quality of the retinal image for positive (high luminance) in comparison to negative (low luminance) polarity displays.

However, some other studies failed to find such a positive polarity advantage (Cushman 1984, 1986, Legge *et al*. 1985, 1987, Creed *et al*. 1988, Pastoor 1990, Shieh 2000, Wang and Chen 2000). Insufficient statistical power due to small sample sizes might have been one reason for some of these null findings (e.g. Legge *et al*. 1985, with n = 6, Legge *et al*. 1987, with n = 5). Another reason why a positive polarity advantage was not always observed might be of a technical nature. Almost all null findings (with Shieh 2000 as the only exception) were observed with cathode-ray tube (CRT) displays. Positive polarity CRT displays with a white background presented with standard refresh rates of 60 Hz are particularly prone to the problem of flicker (Pawlak 1986, Creed *et al*. 1988). Flicker, in turn, promotes visual fatigue and decreases performance. In contrast, with negative polarity, the display is predominantly dark so that the flicker problem of CRT monitors with standard refresh rates would be less of an issue. Given that CRT displays are increasingly replaced by new display technologies, such as thin film transistor liquid-crystal displays (TFT-LCDs), which lack the flicker problem, the existing empirical evidence suggests that one should use positive polarity displays in order to increase the speed and accuracy of information extraction from these displays.

Within the past few years, fast-paced developments have enabled the use of TFT-LCDs not only as

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replacements of CRT monitors but also as standard devices in various other fields of application. For example, transmissive-type TFT-LCDs are about to replace traditional (incandescent-type) dashboard instruments in cars, where they already serve as large (from 4.3″ to 17″) and bright displays of navigation devices and on-board computers. The new opportunities and advantages of these displays notwithstanding, it is clear that there may also be risks. For instance, due to their potentially high luminance and their possibility to display a wide array of colours, TFT-LCDs may affect dark adaptation during night-time driving to a much larger extent than analogue dashboard instruments with their parsimonious use of lighting and their very limited range of colours. In addition, the spectral distribution underlying the perception of colour is different between TFT-LCDs and earlier display techniques. Whereas unfiltered incandescent light sources can be characterised by a relatively continuous spectral distribution with maximum values in the far end of the visual spectrum, TFT-LCDs have several spectrally narrow peaks. So far, it is not known whether and, if so, to what extent the TFT-LCD technique poses a problem under night-time driving conditions. What is needed before TFT-LCDs can be recommended as the standard display technique in automotive design is basic experimental research that allows for a first assessment of this technique's potential to impair dark adaptation. Given the expense and effort of ergonomic research, a fine-grained analysis based on a range of model-specific lighting parameters would be indicated if this first assessment revealed a general cause for concern that TFT-LCDs may impair dark adaptation (in addition to model-specific display characteristics (such as luminance, colour, layout and lighting source), ambient illumination values from inside and outside the car, as well as lighting parameters of the target to be detected, would also have to be considered as factors). Accordingly, the experiments reported in this article were run with the purpose to provide a first experimental basis for decisions about in-car TFT-LCDs with regard to two variables of display design, that is, display polarity and display colour.

Turning first to the display polarity variable, the brightness of positive polarity displays is larger than that of negative polarity displays. The higher brightness of positive polarity displays (e.g. black text on white background) is known to facilitate information extraction relative to negative polarity displays (e.g. white text on black background). Unfortunately, high levels of brightness may at the same time impair dark adaptation and thus cause problems when peripheral low-contrast objects must be detected during night-time driving.

In experiment 1, participants sat in a dark room and performed a brief discrimination task on a simulated control panel on which text was presented either in positive (black-on-white) or in negative (white-on-black) polarity. Performance in the control panel discrimination task was expected to be better for positive than for negative polarity displays, replicating the typical positive-polarity advantage. At frequent intervals, participants tried to detect low intensity achromatic stimuli displayed on a distant screen in an attempt to simulate the detection of low-contrast objects during night-time driving. The question was whether low-contrast object detection performance would be impaired by the positive as opposed to the negative polarity control panel display.

2. Experiment 1

2.1. *Method*

2.1.1. *Participants*

Participants were 85 adults, 23 of whom were male. Participants ranged in age from 18 to 45 years (mean = 24.05). All except six were students. Participants received a partial course credit. All participants reported normal or corrected-to-normal visual acuity and normal colour vision.

2.1.2. *Material and task*

The experiment took place in a dark room without any exposure to daylight and no external light source other than the TFT-LCD display and the projector light. Ambient illumination at the participants' eye position (measured with a Gossen Mavolux 5032 B illuminance meter with class B accuracy according to DIN 5032–7; Gossen Foto- and Liehtmesstechnik GmbH, Nürnberg, Germany) was 0.13 lx when the red, green and blue colour space coordinates (RGB) values of the TFT-LCD display were set to (0, 0, 0) and the projector presented an entirely black image on to the projection screen. Display luminance at this RGB value was 0.4 cd/m^2.

The control panel discrimination task was presented on the 15″ (1024 × 768 pixels) TFT-LCD matte display cold cathode fluorescent lamp (CCFL) backlight of an Apple PowerBook computer (Apple Inc., Cupertino, CA, USA), which also controlled the experiment. The viewing distance was 80 cm. Participants sat on a height-adjustable chair so that their eyes were 122 cm above the floor. The display was positioned at a height of 74 cm. The display inclination of 106° accommodated the participant's raised eye position. The control panel presented on the display depicted three circular analogue-like indicators, a combined temperature and fuel gauge on the left, a speed indicator in the middle and a tachometer on the right with diameters of 9.5 cm (6.80°), 10.5 cm (7.51°) and 9.5 cm (6.80°), respectively. Together, the three indicators covered an area of about 26.7 cm × 16.0 cm (18.95° × 11.42°). In the positive polarity condition, the indicator discs were presented in white, with numbers, display ticks and contours in black. In the negative polarity condition, the indicators were presented in black, with numbers, display ticks and contours in white (see Figure 1). The area around the indicators was always black. For white and black, the RGB values were set to (255, 255, 255) and (0, 0, 0), respectively. Figure 2 displays the spectral power distribution of the TFT-LCD display for white. Table 1 displays the luminance (cd/m^2) and the chromaticity coordinates (xy values) of the display as well as the illuminance at eye position (lx) for the positive and the negative polarity conditions.

For the low-contrast object detection task, low intensity (and, hence, low-contrast) achromatic targets were presented on a hemispherical projection screen with a diameter of 150 cm (VisionStation 1024 XL; Elumens Corporation, Cary, NC, USA). The image was projected by an Epson PowerLite 730c data projector (Epson America, Inc., Long Beach, CA, USA) equipped with a 180° spherical lens (TruTheta®; Elumens Corporation, Cary, NC, USA). The projector was placed in a tray below the desktop on which the display was positioned. The centre of the projection screen was marked by a fixation cross, which appeared at a viewing distance of 122 cm and at a height of 112 cm. The stimuli were small ovals of 1.8 cm × 2.1 cm (0.85° × 0.97°). The targets were presented in an area of 33 cm × 37 cm (15.40° × 17.25°) around the fixation cross. No targets could appear in an area of 8.5 cm × 9.5 cm (4.00° × 4.46°) around the fixation cross because the experiment was focused on peripheral rod vision sensitivity and its possible impairment due to display illumination. Participants were instructed to detect peripheral targets while focusing the fixation cross but eye movements were not controlled.

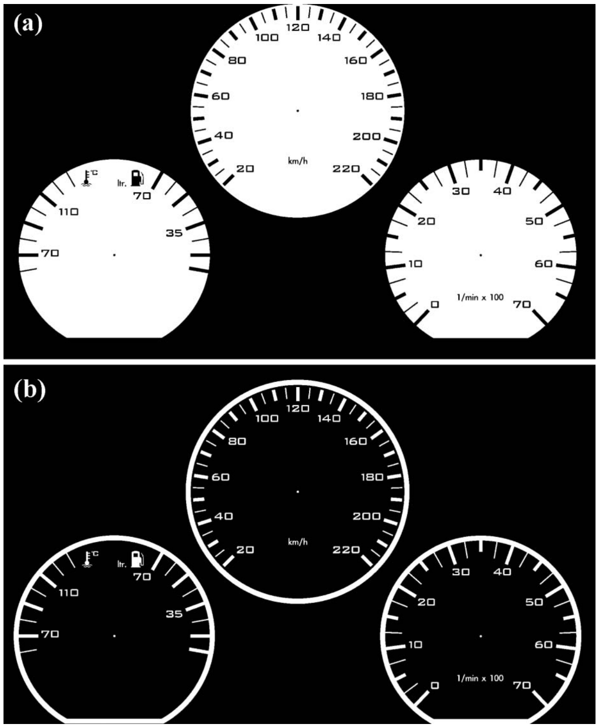

Figure 1. The control panel display used in all three experiments depicted in the positive (a) and the negative (b) polarity variant.

In the control panel discrimination task, each trial comprised six successive presentations of words that were either presented correctly or with their letters in reversed order. The words were selected from a set of 208 five-letter nouns with a written word frequency above 100 (Baayen *et al.* 1993). Words and their letter-reversed counterparts were presented at one of 14 possible positions in one of the three circular analogue displays on the display. The words covered an area of about 1.5 cm × 0.4 cm (1.07° × 0.29°). For each presentation, the word and its position were sampled at random with replacement. The word was presented in correct or in reversed letter order with a probability of 0.5. Presentation duration was 2000 ms, with intervals of 500 ms between presentations, amounting to 15 s

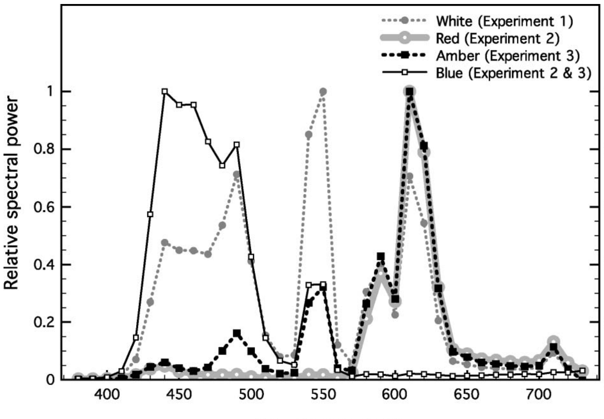

Figure 2. Relative spectral power distributions of the display colours in experiment 1 (white), experiment 2 (red and blue), and experiment 3 (amber and blue) measured with an Eye-One Pro spectrophotometer (GretagMacbeth AG, Regensdorf, Switzerland) in 10 nm steps. For the sake of clarity, the relative spectral power distribution of blue measured in experiment 3 was omitted as it was not distinguishable from the one measured in experiment 2. Available in colour online

Table 1. Luminance values and chromaticity coordinates of the laptop display and illuminance at eye position as a function of polarity and colour.

		Chromaticity coordinates		Illuminance at eye position	
	Display luminance	*x*	*y*	Positive polarity	Negative polarity
Experiment 1					
White	125.49 cd/m^2	0.314	0.330	3.73 lx	0.67 lx
Experiment 2					
Red	21.99 cd/m^2	0.601	0.339	0.87 lx	0.26 lx
Blue	21.87 cd/m^2	0.156	0.134	0.83 lx	0.26 lx
Experiment 3					
Amber	21.70 cd/m^2	0.524	0.387	1.00 lx	0.26 lx
Blue	21.40 cd/m^2	0.155	0.133	0.78 lx	0.24 lx

Note: Display luminance was measured with a *Mavolux 5032 B* illuminance meter (Gossen, Class B accuracy according to DIN 5032–7) equipped with a luminance attachment. Chromaticity coordinates were measured with an *Eye-One Pro* spectrophotometer (GretagMacbeth). Illuminance at eye position was measured with the *Mavolux 5032 B* illuminance meter.

for each trial of the control panel discrimination task. The participants pressed a button, as quickly as possible, on a hand-held response box plugged into the computer when a word was presented with its letters in reversed order. Participants were not to respond when a word was presented correctly. Responses to correct words were counted as false alarms.

Each trial of the low-contrast object detection task comprised 12 intervals of 2500 ms duration. For each interval, it was determined randomly whether a target was presented (with probability 5/6) or whether the interval stayed blank (1/6). There was a 500 ms pause between intervals, during which no targets were presented. In sum, each trial comprising 12 intervals lasted 36 s. Targets were defined as luminance increments of three different levels ((7, 7, 7), (8, 8, 8) and (9, 9, 9) in terms of RGB values relative to the (0, 0, 0) black background, which corresponded to 0.15 lx, 0.16 lx and 0.17 lx, respectively, as measured at eye position with the Gossen Mavolux 5032 B illuminance meter. (Brightness measurement of the low intensity targets projected to the hemispherical screen was difficult as a direct measurement at the screen was impossible. Positioning the measurement device in front of the screen would have interfered with the projection itself. It was therefore decided to measure illumination at eye position. However, due to the low intensity of targets, the measurement device was not sensitive enough to differentiate between a 1.8 cm × 2.1 cm target at a distance of 122 cm when projected in RGB values (7, 7, 7), (8, 8, 8) or (9, 9, 9) and, basically, this measurement did not differ from the illuminance value when the projector was in dark mode, that is, 0.13 lx. It was therefore decided, for measurement purposes only, to illuminate the whole projection screen with the respective RGB value. Illuminance at eye position was 0.15, 0.16, 0.17 for RGB (7, 7, 7), (8, 8, 8) and (9, 9, 9), respectively. Given the described operationalisation, the measurement is an overestimation of the actual brightness.) Occasional blank intervals made it possible to determine detection sensitivity. Targets were presented for 100 ms. Target onset was determined randomly with the restriction that both the 100 ms target and a 1000 ms response window fitted into the limits of the interval. This implies that the earliest starting point of a stimulus presentation was at time point 0 ms within an interval and the latest starting point was at time point 1400 ms. Whenever participants detected a target, they were to press the response button as quickly as possible. Participants were not informed about the target presentation characteristics (i.e. the existence and duration of filled vs. blank intervals).

2.1.3. *Procedure*

Participants were tested individually. They were seated in front of the display and received standardised auditory instructions. Participants were informed about the control panel discrimination task and the low-contrast object detection task. They saw a visual demonstration of each of the two tasks. The participants were informed that a car horn would indicate that they needed to switch from the control panel discrimination task to the low-contrast object detection task and that a bell sound would indicate that they had to switch back from the detection task to the control panel discrimination task. Instructions took about 5 min, during which participants' vision started to adapt to the dark room, dimly illuminated by the display and the light emitted by the projector displaying a 'black' (0, 0, 0 in RGB values) background on to the hemispherical projection screen. Following the instructions, participants dark-adapted for another 5 min, this time by being exposed to an entirely black display.

Shortly before the end of the dark-adaptation period, participants were auditorily informed that testing would now begin. After the ringing of the first bell, the display shown in Figure 1 faded in and the control panel discrimination task began. Words and their letter-reversed counterparts were presented. After 15 s, the car horn indicated the beginning of the low-contrast object detection task, during which the display stayed turned on. Participants were told to focus on the fixation cross in the centre of the hemispherical projection screen.

For each polarity condition, there were 10 sequences of the control panel discrimination and the low-contrast object detection task. After the 10th block, the display turned black and the participant was told to wait. After 2-min break, the display was presented again, this time in the other polarity condition. Again, participants received 10 sequences of the control panel discrimination and the low-contrast object detection task. The sequence of polarity conditions (positive–negative vs. negative–positive) was randomly determined. At the end of the final target detection trial, all participants were informed about the purpose of the experiment. The experiment lasted about 35–40 min.

2.1.4. *Design*

The experiment comprised a one-factorial design with display polarity (positive vs. negative) as within-subject variable. To reduce data complexity, responses in the low-contrast object detection task were averaged across the three brightness levels. The dependent variables were participants' discrimination sensitivity (P_r = hits − false alarms) and average reaction time in the control panel word discrimination task as well as detection sensitivity (P_r) in the low-contrast object detection task.

In order to detect a small to medium effect of display polarity (as defined by Cohen 1988), that is, an effect of size $f = 0.20$, given a population correlation of $\rho = 0.5$ between the two levels of the independent variable and desired levels of $\alpha = \beta = 0.05$, data had to be collected from a sample of at least n = 84 participants (Faul *et al.* 2007, 2009). Data were collected from n = 85 participants. The level of alpha was maintained at 0.05 for all statistical decisions. A multivariate approach was used for all within-subjects comparisons. All multivariate test criteria correspond to the same (exact) F statistic, which is reported.

2.2. *Results*

2.2.1. *Control panel discrimination task*

The means of participants' discrimination sensitivity and average reaction times are presented in Figures 3 and 4, respectively. Figure 3 (left columns) shows that sensitivity when discriminating words from their letter-reversed counterparts was larger for positive than for negative polarity displays. Similarly, reaction times were faster for positive than for negative polarity displays (Figure 4, left columns).

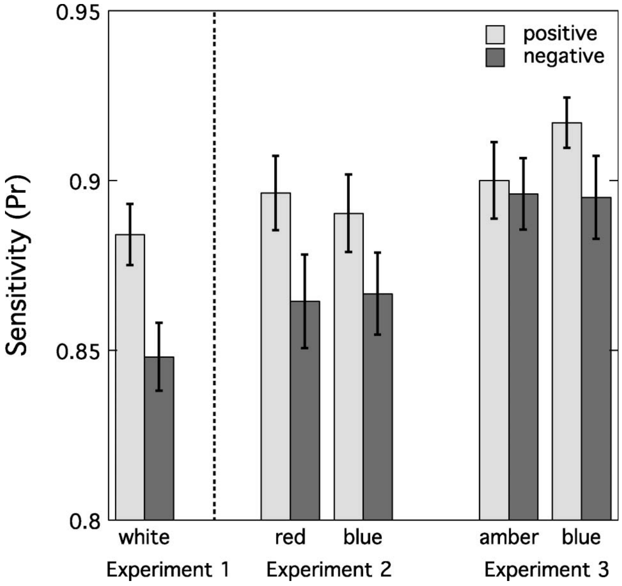

Figure 3. Sensitivity (P_r) in the control panel word discrimination task as a function of display polarity (experiment 1) and of display polarity and display colour (experiments 2 and 3). The error bars depict the standard errors of the means.

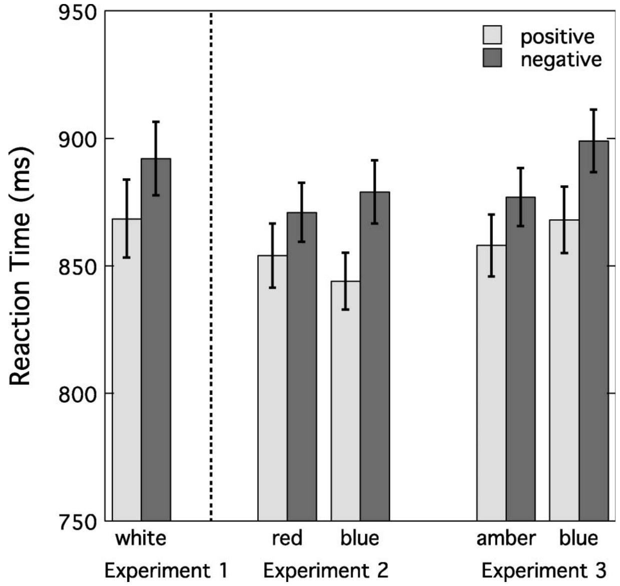

Figure 4. Average reaction times in the control panel word discrimination task as a function of display polarity (experiment 1) and of display polarity and display colour (experiments 2 and 3). The error bars depict the standard errors of the means.

A one-factorial multivariate ANOVA (MANOVA) of the sensitivity data with polarity (positive vs. negative) as within-subject variable revealed a significant main effect of polarity, $F(1, 84) = 9.05$, $p < 0.01$, $\eta^2 = 0.10$, confirming that indeed discrimination performance was better with positive than with negative polarity displays. An analogous analysis of the reaction time data revealed a parallel positive polarity advantage. Participants were faster with positive than with negative polarity displays, $F(1, 84) = 6.49$, $p = 0.01$, $\eta^2 = 0.07$.

2.2.2. *Low-contrast object detection task*

The means of participants' target detection sensitivity are presented in Figure 5 (left columns). Detection sensitivity was larger for negative than for positive polarity displays. A one-factorial MANOVA of the sensitivity data confirmed that this positive polarity disadvantage was statistically significant, $F(1, 84) = 407.77$, $p < 0.01$, $\eta^2 = 0.83$.

2.3. *Discussion*

Experiment 1 revealed a typical positive polarity advantage in that discrimination performance on the display simulating a car control panel was better when words were presented in dark letters on a light background (positive polarity), compared with a presentation in light letters on a dark background (negative polarity). This positive polarity advantage is consistent with existing research (Bauer and Cavonius 1980, Radl 1980, Magnussen *et al.* 1992, Hall and Hanna 2004, Chan and Lee 2005, Buchner and Baumgartner 2007). Presumably, the advantage is caused by the typically higher luminance of positive relative to negative polarity displays leading to a smaller pupil size, which, in turn, yields a greater depth of field and less spherical aberration (Buchner *et al.* 2009). This fits with the display parameters of experiment 1, in which illumination was 3.73 lx and 0.67 lx for the positive and the negative polarity condition, respectively.

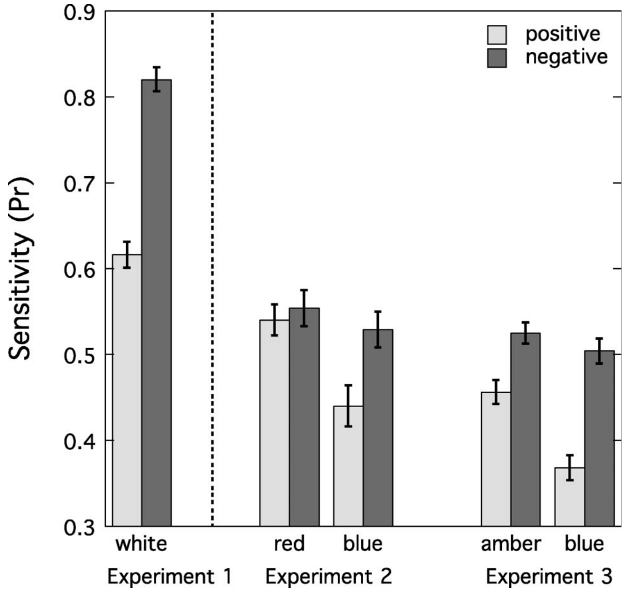

Figure 5. Sensitivity (P_r) in the low-contrast object detection task as a function of display polarity (experiment 1) and of display polarity and display colour (experiments 2 and 3). The error bars depict the standard errors of the means.

The data of experiment 1 also show that positive polarity displays can have serious disadvantages in that low-contrast object detection is worse after read-out from positive compared with negative polarity control panels. The simplest explanation for this disadvantage is that the higher luminance associated with positive polarity displays has detrimental effects on dark adaptation. As a consequence, low-contrast objects are harder to detect after having scanned such a positive polarity display simulating a car control panel.

At first glance, the trade-off between display legibility and low-contrast object detection sensitivity may seem inevitable. The brighter the to-be-read display, the more detrimental should be its after-effect on dark adaptation and, hence, on low-contrast object detection. However, there may be display properties that allow for unimpaired dark adaptation after scanning positive polarity displays. The scanning of an illuminated display for detailed information is primarily accomplished by foveal cone vision, whereas detecting low-contrast objects in the distant periphery is primarily achieved by peripheral rod vision. The spectral sensitivity of cone and rod vision differs, with cone vision having a maximum spectral sensitivity at around 550 nm and rod vision having a maximum sensitivity shifted to the short-wave end at about 500 nm. Thus, if the display is restricted to emit only light near the long-wave end of the visible spectrum (red), then it may still be possible to observe a positive polarity advantage when detailed information has to be read from the display while avoiding the detrimental effects on dark adaptation of the rods, thus minimising the negative effects of the control panel display on the ability to detect low-contrast peripheral objects in the distance.

This idea is, of course, not new. Aviation researchers in the late 1960s and 1970s were interested in the post-exposure effects of different types of aircraft instrument illumination on scotopic absolute and acuity thresholds (Reynolds and Grether 1968, Reynolds 1971). The simulation study by Reynolds and Grether (1968) revealed a small advantage that incandescent red illumination had compared with unfiltered white and blue-filtered white. With low control panel luminance (0.03 cd/m^2), the advantage was weak and only visible in scotopic acuity thresholds, not in scotopic absolute thresholds. With higher panel luminance (0.17 cd/m^2), the advantage of red over white was present in both dependent measures. A follow-up study (Reynolds 1971) compared the post-exposure effects of electroluminescent white, green and yellow panel lighting with those of incandescent red. Again, red lighting at a panel luminance of 0.17 cd/m^2 resulted in the lowest absolute and acuity thresholds, even though the effects were argued to be 'quite small for practical purposes' (Reynolds 1971, p. 38).

However, the small advantage of red light documented in the literature is based on the use of incandescent light sources, which are usually characterised by a more continuous, gently inclined spectral distribution with maximum values in the far end of the visual spectrum. Red illuminated displays may have been less detrimental to rod dark adaptation than display colours from the short-wave end of the spectrum because the former overlap less with the area of maximal rod sensitivity than the latter. Nevertheless, the presumably more gently inclined spectrum underlying red incandescent illumination may not entirely spare the sensitivity spectrum of rod vision and may therefore interfere with rod dark adaptation to a certain extent. In contrast, red TFT-LCDs with a spectrally narrow peak in the range of 610 nm have a very small extent of overlap with the rod sensitivity spectrum and, as such, should have very small or even no effects on rod dark adaptation. TFT-LCD illumination may thus yield a larger red-light advantage. In addition, modern TFT-LCDs may also be much brighter than the control panels considered four decades ago, particularly with positive polarity displays with large areas of bright background. The increase in brightness may boost the advantage of red (e.g. over blue) displays as in the studies mentioned in the previous paragraph, but it may also reduce or even eliminate the possibly lower interference potential of red light emitted by TFT-LCDs if a 'red' TFT-LCD emits sufficient energy in the region in which the rods are sensitive. In essence, then, it is an open question whether or not TFT-LCDs would yield a red-light advantage on the detection of low-contrast objects. The purpose of experiment 2, therefore, was to test this question empirically.

More specifically, experiment 2 tested whether red TFT-LCD illumination would preserve dark adaptation of the rods. To this end, detection performance for distant peripheral low-contrast objects was compared after adapting to equally bright red and blue control panel TFT-LCDs. The blue colour was expected to be maximally detrimental to the human scotopic detection of low-contrast objects because the emission spectrum of the TFT-LCD blue light overlaps with the point of maximum spectral sensitivity of the rods in the human eye. Display polarity was manipulated as in experiment 1. As before, a positive polarity advantage was expected for the control panel discrimination task. In contrast, low-contrast object detection should be worse with positive than with negative polarity displays, but more so for blue than for red displays. For red displays, negative effects of positive polarity displays on the detection of low-contrast peripheral objects might even be absent.

3. Experiment 2

3.1. *Method*

3.1.1. Participants

Participants were 76 adults, 15 of whom were male. Participants ranged in age from 18 to 40 years (mean = 24.07). All but two were students. Participants were either paid for their participation or received partial course credit. All participants reported normal or corrected-to-normal visual acuity and normal colour vision.

3.1.2. Material, task and procedure

Materials, task and procedure were the same as in experiment 1 with the following exceptions. Display colour was manipulated and could be red or blue. In order to attain equivalent luminance levels, the red and blue display colours were adjusted to RGB values of (249, 0, 0) and (0, 0, 255), respectively. Figure 2 displays the spectral power distributions of the TFT-LCD for both colours. Table 1 displays the luminance values and chromaticity coordinates of both colours measured at the display as well as the illuminance of all four colour × polarity combinations measured at eye position. Participants completed four blocks, one of each colour × polarity combination. The order of blocks was randomly determined.

Given that low-contrast object detection performance was rather high in experiment 1 ($P_r > 0.80$ for the negative polarity condition), the brightness (and, hence, contrast) of the low-contrast stimuli was reduced from RGB values of (7, 7, 7), (8, 8, 8) and (9, 9, 9) to (6, 6, 6), (7, 7, 7) and (8, 8, 8), which was equivalent to 0.14 lx, 0.15 lx and 0.16 lx, respectively, as measured at eye position.

3.1.3. Design

The experiment comprised a two-factorial design with display polarity (positive vs. negative) and display colour (red vs. blue) as within-subject variables. The dependent variables were participants' discrimination sensitivity (P_r) and average reaction time in the control panel discrimination task as well as detection sensitivity (P_r) in the low-contrast object detection task.

The difference in the size of the polarity effect (positive polarity – negative polarity) between the red and the blue display colour was relevant for the *a priori* power considerations. In order to detect a small to medium effect (as defined by Cohen 1988) in this difference, that is, an effect of size $f = 0.20$, given a population correlation of $\rho = 0.5$ between the two levels of the independent variable and desired levels of $\alpha = \beta = 0.05$, data had to be collected from a sample of at least n = 84 participants (Faul *et al.* 2007, 2009). Data were collected from n = 76 participants so that the power was slightly smaller than the aim with $1 - \beta = 0.93$. The level of alpha was maintained at 0.05 for all statistical decisions.

3.2. *Results*

3.2.1. Control panel discrimination task

The means of participants' discrimination sensitivity and average reaction times are presented in Figures 3 and 4, respectively. Figure 3 (central columns) shows that the sensitivity was larger for positive than for negative polarity displays, whereas colour did not influence performance. Similarly, reaction times were faster for positive than for negative polarity displays, independent of the display colour (Figure 4, central columns).

A 2 × 2 MANOVA of the sensitivity data with polarity (positive vs. negative) and colour (red vs. blue) as within-subject variables revealed a significant main effect of polarity, $F(1, 75) = 9.49$, $p < 0.01$, $\eta^2 = 0.11$, but neither a main effect of colour, $F(1, 75) = 0.04$, $p = 0.85$, $\eta^2 < 0.01$, nor an interaction between colour and polarity, $F(1, 75) = 0.20$, $p = 0.66$, $\eta^2 < 0.01$.

An analogous analysis of the reaction time data revealed a parallel pattern of results. There was a significant main effect of polarity, $F(1, 75) = 13.79$, $p < 0.01$, $\eta^2 = 0.16$, but neither a main effect of colour, $F(1, 75) = 0.04$, $p = 0.85$, $\eta^2 < 0.01$, nor an interaction between these variables, $F(1, 75) = 3.49$, $p = 0.07$, $\eta^2 = 0.04$, even though the latter effect was close to significance.

3.2.2. Low-contrast object detection task

The means of participants' target detection sensitivity are presented in Figure 5 (central columns). Detection was better for negative than for positive polarity displays and also for red than for blue colour displays. In addition, the influence of polarity was absent for red displays.

A 2 × 2 MANOVA of the sensitivity data with polarity (positive vs. negative) and colour (red vs. blue) as within-subject variables revealed a significant main effect of polarity, $F(1, 75) = 48.58$, $p < 0.01$, $\eta^2 = 0.39$, a main effect of colour, $F(1, 75) = 56.60$, $p < 0.01$, $\eta^2 = 0.43$, as well as an interaction between polarity and colour, $F(1, 75) = 16.00$, $p < 0.01$, $\eta^2 = 0.18$. *Post-hoc t*-tests using the Bonferroni–Holm method of protecting against α-error accumulation (Holm 1979) showed that there was a positive polarity disadvantage for blue displays, $t(75) = 8.58$, $p < 0.01$, $\eta^2 = 0.49$, but none for red displays, $t(75) = 1.06$, $p = 0.29$, $\eta^2 = 0.01$.

Immediately after testing, a subset of the participants (n = 45) responded to three questions: (1) Which colour was more comfortable while working on the control panel discrimination task? (2) Which colour made working on the control panel discrimination task easier? (3) Which colour interfered more with low-contrast object detection? Four participants failed to respond appropriately and a certain number of participants did not favour one colour over the other as a response to one of these questions. These responses were not analysed. Participants showed a clear preference of blue (n = 31) over red (n = 10) in the control panel discrimination task (question 1), $\chi^2(1) = 10.76$, $p < 0.01$. There was no agreement on whether red (n = 18) or blue (n = 13) was easier to work with in the control panel discrimination task (question 2), $\chi^2(1) = 0.81$, $p = 0.37$. Finally, most participants (incorrectly) believed that red (n = 24) interfered more than blue (n = 9) with low-contrast object detection (question 3), $\chi^2(1) = 6.82$, $p < 0.01$.

3.3. *Discussion*

Experiment 2 replicated a positive polarity advantage in the control panel discrimination task in terms of both accuracy and response speed and independent of display colour. For the low-contrast object detection task, in contrast, blue positive polarity displays seem to have impaired dark adaption more than blue negative polarity displays, whereas red displays interfered less with object detection performance than blue displays. Additionally, there was no difference in object detection performance between red positive and red negative polarity displays.

Based on the objective performance data of experiment 2, red displays should be preferred. Red displays provide for a positive polarity advantage when information has to be extracted from the display while avoiding the positive polarity disadvantage in the detection of low-contrast objects in the distant periphery, presumably by preserving rod dark adaptation. However, the subjective judgements made by the participants disagree with objective performance. Red displays were unpopular among participants. They (incorrectly) judged red displays to be less comfortable to work with and more interfering when detecting low-contrast objects than blue displays. Similar findings have been reported elsewhere. For example, in a simulated night-time driving experiment, Galer and Simmonds (1985) tested panel display reading ability and subjective preference of five different display colours. The authors found differences with regard to subjective measures such as attractiveness, general preference and choice for own car. Blue/green, green and yellow displays were preferred, whereas red displays were not liked or even disliked. The dislike of red displays may have a physiological basis. The focal point of long wavelengths (such as red) is farther behind the retina than that of short wavelength light. This implies that more accommodation is necessary for long wavelength light in order to bring the visual image into focus (Lin *et al.* 2008). Increased accommodation effort over time presumably leads to visual fatigue. It seems possible that the subjective questionnaire data captured that aspect.

Given that red displays would be a good choice from an objective performance point of view while at the same time they receive comparatively low ratings in the subjective judgements, the question suggests itself whether a display colour exists that preserves rod dark adaptation and, simultaneously, meets with the users' approval.

Experiment 3 was run to test amber as an alternative candidate of display colour. In TFT-LCDs, amber consists of a 2:1 weighted mixture of red and green light. Performance in an amber display condition was compared with performance in a blue display condition, the latter being identical to the blue display condition in experiment 2. It was expected to replicate the positive polarity advantage for the control panel discrimination task and, for the blue display, a positive polarity disadvantage in the low-contrast object detection task. Ideally, no such disadvantage should be observed with the amber display colour while, at the same time, subjective ratings should show that blue is not preferred over amber (or perhaps even that amber is preferred over blue).

4. Experiment 3

4.1. Method

4.1.1. Participants

Participants were 80 adults, 13 of whom were male. Participants ranged in age from 19 to 41 years (mean = 24.19). All of them were students. Participants received partial course credit. All participants reported normal or corrected-to-normal visual acuity and normal colour vision.

4.1.2. Material, task, and procedure

Materials, task and procedure were the same as in experiment 2 with the following exceptions. Instead of the red display colour, amber displays with RGB values of (196, 98, 0) were used. The blue colour was the same as in experiment 2 with RGB values of (0, 0, 255). Figure 2 displays the spectral power distributions of the TFT-LCD for both colours and Table 1 displays their luminance values and the chromaticity coordinates as measured at the display, as well as the illuminance of all four colour × polarity combinations measured at eye position.

4.1.3. Design

As in experiment 2, a two-factorial design was used with display polarity (positive vs. negative) and display colour (amber vs. blue) as within-subject variables.

Data were collected from n = 80 participants so that, given the parameter values assumed in experiment 2, the power was slightly smaller than the aim, with $1 - \beta = 0.94$ (Faul *et al.* 2007, 2009). The level of alpha was maintained at 0.05 for all statistical decisions.

4.2. Results

4.2.1. Control panel discrimination task

The means of participants' discrimination sensitivity and average reaction times are presented in Figures 3 and 4, respectively. Figure 3 (right columns) shows that the sensitivity was somewhat larger for positive than for negative polarity displays, a tendency that seemed to be stronger for blue displays. Reaction times were faster for positive than for negative polarity displays and also faster for amber than for blue displays (Figure 4, right columns).

A 2 × 2 MANOVA of the sensitivity data with colour (amber vs. blue) and polarity (positive vs. negative) as within-subject variables revealed no significant main effect of polarity, $F(1, 79) = 1.74$,

$p = 0.19$, $\eta^2 = 0.02$, no effect of colour, $F(1, 79) = 0.71$, $p = 0.40$, $\eta^2 = 0.01$ and no interaction between polarity and colour, $F(1, 79) = 1.07$, $p = 0.31$, $\eta^2 = 0.01$.

An analogous analysis of the reaction time data revealed a significant main effect of polarity, $F(1, 79) = 19.29$, $p < 0.01$, $\eta^2 = 0.20$, a main effect of colour, $F(1, 79) = 9.19$, $p < 0.01$, $\eta^2 = 0.10$, but no interaction between these variables, $F(1, 79) = 1.14$, $p = 0.29$, $\eta^2 = 0.01$.

4.2.2. *Low-contrast object detection task*

The means of participants' detection sensitivity are presented in Figure 5 (right columns), which shows that detection was better for negative than for positive polarity displays and also for amber than for blue colour displays. In addition, the influence of polarity seemed to be reduced for amber displays.

A 2 × 2 MANOVA of the sensitivity data with polarity (positive vs. negative) and colour (amber vs. blue) as within-subject variables revealed a significant main effect of polarity, $F(1, 79) = 258.13$, $p < 0.01$, $\eta^2 = 0.77$, a main effect of colour, $F(1, 79) = 44.43$, $p < 0.01$, $\eta^2 = 0.36$ and an interaction between polarity and colour, $F(1, 79) = 35.18$, $p < 0.01$, $\eta^2 = 0.31$. *Post-hoc* t-tests using the Bonferroni–Holm method of protecting against α-error accumulation (Holm 1979) showed that there was a polarity effect for blue displays, $t(79) = 15.91$, $p < 0.01$, $\eta^2 = 0.76$, as well as for amber displays, $t(79) = 7.99$, $p < 0.01$, $\eta^2 = 0.44$. In terms of the standardised effect size index η^2 the positive polarity disadvantage for amber displays was much smaller than that of blue displays, but both effects were fairly large.

In the post-experimental questionnaire similar to experiment 2, all participants were asked three questions: (1) Which colour was more comfortable while working on the control panel discrimination task? (2) Which colour made working on the control panel discrimination task easier? (3) Which colour interfered more with low-contrast object detection? A certain number of participants did not favour one colour over the other as a response to one of these questions. As in experiment 2, these responses were not analysed. With regard to the first and second question, the remaining sample of participants showed no clear preference for either of the two colours. A total of 42 participants evaluated amber as being more comfortable than blue, whereas 34 preferred blue over amber (question 1), $\chi^2(1) = 0.84$, $p = 0.36$. A total of 39 participants evaluated amber as being easier to work with than blue, whereas 26 preferred the blue over amber (question 2), $\chi^2(1) = 2.60$, $p = 0.11$. With regard to the third question, most participants (correctly) assessed the blue display colour to interfere more with low-contrast object detection than the amber display colour (48 vs. 23), $\chi^2(1) = 8.80$, $p < 0.01$.

4.3. *Discussion*

Experiment 3 again replicated a positive polarity advantage for the control panel discrimination task, at least in terms of response speed. The detection of peripheral low-contrast objects was again better for negative than for positive polarity displays. However, low-contrast object detection was particularly impaired with blue positive polarity. With amber displays, the positive polarity disadvantage on low-contrast object detection was reduced, but still clearly present.

With regard to subjective evaluation, there was no preference for blue displays in comparison with amber displays as there had been a preference for blue relative to red displays in experiment 2. Quite to the contrary, participants believed that the amber colour was less interfering with object detection in the distance. This subjective judgement was in agreement with the actual performance data.

5. General discussion

The work reported here was intended to provide a first solid empirical basis for judgements about the effects of TFT-LCDs with regard to two variables of interest, display polarity and display colour. The influences of these two variables on reading performance and scotopic sensitivity have already been of interest in past research. For example, positive polarity effects have been repeatedly documented for reading from CRT monitors (for a review, see Pawlak 1986). Also, a red display advantage on scotopic sensitivity has been observed under incandescent illuminating conditions (e.g. Reynolds and Grether 1968, Reynolds 1971), but it seemed small and the results were based on the use of incandescent light sources, which are usually characterised by a presumably more continuous, gently inclined spectral distribution that overlaps with the human rod sensitivity spectrum. In contrast, state-of-the-art TFT-LCDs have spectrally narrow peaks and – for the case of red lights – should have a smaller degree of overlap with the human rod sensitivity spectrum than incandescent light sources. Red TFT-LCD display illumination may thus yield a larger red light advantage than incandescent red light illumination. However, modern TFT-LCDs tend to be much brighter than the control panels considered four decades ago, particularly with positive polarity displays with large areas of bright background. This may increase, reduce or even eliminate the possibly lower interference potential of the red light emitted by TFT-LCDs. In essence, little is known about the extent to which modern TFT-LCD technique poses particular problems with regard to display polarity and display colour, especially under night-time driving conditions.

The results of the present three experiments were highly consistent in showing that discrimination performance on the display simulating a car control panel was clearly better when words were presented in dark letters on a light background (positive polarity) compared with a presentation in light letters on a dark background (negative polarity). This positive polarity advantage is consistent with existing research (Bauer and Cavonius 1980, Radl 1980, Magnussen *et al*. 1992, Hall and Hanna 2004, Chan and Lee 2005, Buchner and Baumgartner 2007) and is presumably caused by the typically higher luminance of positive relative to negative polarity displays (Buchner *et al*. 2009).

The results of the present experiments were also consistent in showing that low-contrast object detection was generally worse after reading from positive as opposed to negative polarity displays. The simplest explanation for this is that the higher luminance of positive relative to negative polarity displays has detrimental effects on dark adaptation of the rods, as a consequence of which, low-contrast peripheral objects become harder to detect. The problem is particularly severe for blue with considerable positive polarity disadvantages of $\eta^2 = 0.49$ and $\eta^2 = 0.76$ in experiments 2 and 3, respectively. This is not surprising given that the rods have their maximum spectral sensitivity (at about 500 nm) in the vicinity of the emission spectrum of TFT-LCD blue light. However, the problem is notable even for amber displays with a positive polarity disadvantage of $\eta^2 = 0.44$.

Most interestingly, however, there was one exception. No positive polarity disadvantage was observed for red displays ($\eta^2 = 0.01$ in experiment 2). In other words, with red colour displays it seems possible to receive the benefits of positive polarity in information read-out performance without paying the cost in terms of reduced low-contrast object detection sensitivity. The only problem is that red displays were unpopular among participants. They judged red displays to be less comfortable to work with and to be more interfering when detecting low-contrast objects than blue displays, which were preferred. Thus, subjective preferences may be in conflict with choices based on objective performance data, which points to a possible problem when implementing display colours in real car control panels. However, it is not unusual that subjective judgements deviate from objective performance measures. For instance, drivers may report increasing levels of alertness and vigilance at the end of a long daytime drive under monotonous conditions, even though physiological and performance measures show that the opposite is the case (Schmidt *et al*. 2009). From a safety perspective, therefore, results based on objective performance data should be preferred as design guides.

With regard to display colour, the present data are qualitatively similar to earlier results obtained with different display techniques. However, the red display advantage, while statistically significant, was qualified as ‘quite small for practical purposes’ in those studies (Reynolds and Grether 1968, Reynolds 1971). Given a rather large standardised effect size of as much as $\eta^2 = 0.43$ for the difference between blue and red displays on low-contrast object detection in experiment 2, one must necessarily come to a different conclusion. The present authors believe that effects of this size are large enough to cause real concerns.

What one cannot tell at this point, however, is whether the larger display colour effect found here is due to the technical differences between lighting sources (i.e. between TFT-LCDs and earlier incandescent display illuminations) or due to the choice of experimental parameters (e.g. display luminance, ambient illumination, target luminance, etc.). This will have to be the topic of future research in this area. However, the results of the experiments reported here are unambiguous with regard to the general goal outlined in section 1. There is reason for concern that bright positive polarity TFT-LCDs with display colours other than red may impair dark adaptation. It thus seems both justified and necessary to conduct more effortful and more expensive research under more realistic conditions (with moving objects, in a driving simulator, etc.) to assess with a larger degree of ecological validity how big the problem really is.

However, if one wishes to play safe, one may derive practical consequences even from the present laboratory-based effects of display polarity and display colour. For instance, when using TFT-LCDs as car instrument panels, positive polarity red TFT-LCDs are very likely to lead to good instrument readability, while at the same time minimising, relative to other display colours, the negative effects of an illuminated display on low-contrast peripheral object detection. With regard to driving safety, one cannot commit an error when using red, but other display colours, and blue in particular, may lead to safety problems of unknown size.

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