The influence of temporal transitions in coloured road lighting on the visual performance of drivers in mesopic lighting conditions

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Road lighting; coloured lighting; light transition; LED; response time; visual performance; adaptation.
Preface

This report is the final document in the fulfilment for the requirements of the Human-Technology Interaction master program.

During the three-year master program, I came in contact with various subjects, companies and people. Lighting was slowly getting a larger part of this, and in the end, different projects and courses cleared the way towards this lighting graduation project at Philips. The subject of coloured road lighting was relatively new, but had an appealing practical application that constantly kept my interest. Overall, it has been a great opportunity and a pleasure to have the chance to further explore the research and lighting domain.

Of course, I would not have finished this research document without the supervisors during the course of this project. Maurice Donners (Philips), thank you for the input, the developments during the project and making the project happen in the first place. Antal Haans (TU/e) and Ingrid Vogels (TU/e), thank you both for the insights, feedback and ever present willingness to support during the last couple of months. Last but not least, I would like to thank my friends, family and of course Elleke, for their unconditional support.

Ruben Wesselink
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Abstract

Due to the advancements in LED technology, LEDs are increasingly used as a replacement for conventional lighting on roads. One of the benefits is that LED technology is not restricted to a specific light spectrum. This has resulted in a new trend of using coloured road lighting (e.g. red, green, blue), and leads to an increasing variety of lighting on roads. However, these dynamically-changing light levels and colours may increase the visual disturbance to motorists, cyclists, pedestrians and residents (van Bommel, 2015). It is generally known that drivers should not experience great changes in intensity level or uniformity during night-time driving, to keep an optimal and constant level of adaptation for mesopic (low light) vision (Alferdinck, 2010). These new varieties in lighting could therefore hamper adaptation, thereby impairing visibility and resulting in a driver that might be temporarily travelling partially blind.

As there is currently no regulation or guideline applicable to these new lighting features, the effects of temporal changes with these colours are unknown. Of course lighting conditions and transitions can be compared on photometric measures like light levels, uniformity and glare restriction, but these values could be similar to standard LED lighting. It is therefore more valuable to measure and compare lighting on differences in visual performance, like detection threshold, reaction times or target recognition (Eloholma et al., 2005, Halonen & Puolakka, 2010). This study focussed on these type of objective measures and explored whether there is a change in visual performance (i.e. object visibility) after transitions from white to coloured lighting (and reverse) on two different mesopic light level conditions.

Independent variables were the light level (0.15 and 1.0 cd/m²) and the colours in the light transition (red, green, blue, amber, and white). Young participants (23 – 31 years) were asked to sit behind a 1:20 scale model street, and wore shuttered glasses fitted with LEDs, which were used to make the participant adapt to a light colour for 90 seconds. When the shutters opened after adaptation, participants had to respond by using a brake pedal when they saw that an object was present on the model street in front of them. Objective response times and subjective visibility ratings were measured.

Results indicated that coloured lighting transitions had a substantial detrimental effect on the object detection time of participants, although adaptation seemed to have a limited influence on it. The differences in light levels did not result in the expected shorter response times at higher light levels. Participant visibility ratings did not significantly correlate with visual performance for the different colours. There was a trend, although the accuracy was low and practical applicability therefore limited. Transitions ending on blue were found to have the largest detrimental effect on response times. The most favourable lighting was white, followed by the colours red and green.

In this final research document, the theoretical background will be explained. More details regarding the methods that were used will be elaborated upon, and limitations and implications of the experiment on the general topic of outdoor lighting will be discussed. Although further research is required to account for all the variables related to driving outdoors, this first explorative experiment contributes with initial insights regarding coloured road lighting.
# Table of contents

1. **INTRODUCTION**  
   1.1. **PROBLEM SITUATION**  
      1.1.1. Change for sustainability  
      1.1.2. Implementation issues  
      1.1.3. Unintended accidents  
      1.1.4. Regulation & Recommendations  
      1.1.5. Current study  
   1.2. **THEORETICAL FRAMEWORK**  
      1.2.1. Human perception  
      1.2.2. Visibility  
      1.2.3. Models of measurement  
      1.2.4. Night-time driving  
      1.2.5. Chromaticity & Brightness  
   1.3. **PRACTICAL IMPLICATIONS OF THEORY**  
   1.4. **EXPERIMENT HYPOTHESES**  

2. **METHOD**  
   2.1. **DESIGN**  
   2.2. **PARTICIPANTS**  
   2.3. **MANIPULATION**  
      2.3.1. Experiment scenarios  
      2.3.2. Coloured LED lighting  
      2.3.3. Object detection model  
   2.4. **SETTING AND APPARATUS**  
   2.5. **PROCEDURE**  
   2.6. **MEASURES**  

3. **RESULTS**  
   3.1. **DATASET**
3.2. General observations 23

3.3. All white versus mixed light transitions 25

3.4. Direction of mixed light transitions 26

3.5. Blue based light transitions 27

3.6. Experimental full-colour light transitions 29

3.7. High versus low light level transitions 31

3.8. Correlation of subjective and objective measures 32

3.9. Correlation of other measures 34

4. Discussion 35

4.1. General 35

4.2. Main effects 35

4.2.1. Hypothesis 1 – All white versus mixed light transitions 35

4.2.2. Hypothesis 2 – Direction of mixed light transitions 35

4.2.3. Hypothesis 3 – Blue based light transitions 36

4.2.4. Hypothesis 4 – Experimental full-colour light transitions 36

4.2.5. Hypothesis 5 – High versus low light level transitions 37

4.2.6. Hypothesis 6 – Correlation of subjective and objective measures 38

4.3. Specific colour effects 38

4.3.1. Red 38

4.3.2. Green 39

4.3.3. Blue 39

4.3.4. Amber 40

4.4. Limitations and recommendations 40

4.5. Conclusion 43

5. References 45

6. Appendices 51
1. Introduction
Since the invention of the incandescent light bulb, western countries have been installing electric road lighting in their cities. The result of this lighting is very clear; dramatic decreases in number of accidents compared to places that do not have any lighting applied (Wanvik, 2009). The way in which this lighting has been used on roads worldwide has not changed greatly in all these years, as variety in the lighting was limited by technology. It has only been a couple of years since LED technology has matured enough to enter this professional application field as well. This transformed the somewhat conservative field into a fast-changing business, as more people tried to cash in on the LED’s great advantages.

The benefits of using LEDs for road lighting are quite significant. The recyclability of the LED makes them a more sustainable choice, and low energy consumption and increased life expectancy lead to lower energy- and maintenance costs. LEDs can come in different intensities, colour temperatures and even colours, as they are not restricted to a specific spectrum. As a result, a greater variety in lighting systems is nowadays installed on roads. For example, multiple examples of unusual coloured LED road lighting (e.g. red, green or blue) can be found in and around the city of Eindhoven in the Netherlands. As promising as the use of coloured lighting sometimes may be (e.g. less animal disturbance), this variety breaks with the consistency that was found in the pre-LED era. This decreasing consistency leads to significant visual changes in driving conditions. Regulations and road lighting recommendations specific to coloured lighting do not exist. Still, the use of coloured LED road lighting is steadily increasing with little knowledge about the possible deteriorating effects on road safety.

The goal of the present experiment is to test the extent to which transitions between white and coloured lighting, influence object detection. For this purpose, a scale model of a street was used to recreate a near real-life road situation in which such lighting is typically encountered by drivers at night.

1.1. Problem situation
Because road lighting is used everywhere around us, it is important to critically assess new lighting developments for proper future implementation. Most parts of cities and busy roads are lit up to make us feel safe (Pease, 1999), to increase the visibility and guidance during travel, and thereby to reduce accident rates (Wanvik, 2009). This is for a reason, as only 25% of all daily traffic is actually during dark hours, but up to four times more accidents happen during night-time even though artificial lighting is applied (Weijermars, Goldenbeld, Bos & Bijleveld, 2008; Owens & Sivak, 1996). According to Plainis and Murray (2002), these high night-time accident rates are related to reduced visibility and the resulting longer reaction times (at low light levels), although alcohol and fatigue are also a probable cause (Summala & Mikkola, 1994).

1.1.1. Change for sustainability
Although road lighting in general has clear benefits for safety and the ease of orientation for road users, there are negative consequences as well. Lighting all these public roads costs a lot of energy, even when nobody is using them. This leads to both unnecessary financial costs and unneeded light pollution. To cut down on these costs, more lighting is being turned off, dimmed or replaced by LEDs as a replacement for conventional sodium vapour lighting. As road lighting can take up to 70% of the energy usage for local governments (Taskforce Verlichting, 2008) the benefits of LEDs for road authorities explain the rapid expansion of their use. LEDs also typically have a very sharp, cut-off light beam which makes it very useful for controlling the light direction. They are also easy to control individually, and thus allow for intelligent lighting solutions like traffic intensity based lighting. Unfortunately, because
LEDs ongoing rise in efficiency, it is attractive to increase the light level and still save money. Naturally, this gives the opposite effect for light pollution, the trespassing or intrusion of light in unintended areas. This can also be in the form of disability or discomfort glare and sky glow. Sky glow is brightening of the night sky due to the excessive amount of man-made light sources. The misdirection or reflected light of luminaires on objects like greenhouses. monuments, commercial buildings and more, causes real night darkness no longer to be observed (International Dark-Sky Association, 2014). This sky glow not just prevents astronomers from doing observations even far outside urban areas, but it is also linked to adverse health effects. Disruption of circadian rhythms reduces alertness, increases obesity and diabetes and forms of cancers have all been related with it (Haus & Smolensky, 2006; Pauley, 2004).

The correct implementation of road lighting is an important factor in this as well. Where conventional lamps often shatter light in all directions and are thus hard to aim effectively, LED luminaires can provide sharp, cut-off edges. However, white LEDs are more polluting compared to conventional sodium lamps, due to their blue spectral emission (Falchi, Cinzano, Elvidge, Keith, & Haim, 2011). If different colours could help with limiting the disturbance and health effects on humans, coloured road lighting could have a large influence on reducing disturbance.

Beside its influence on humans, the effects of light pollution on ecosystems and animals have been explored as well. Due to increasing awareness for sustainable lighting solutions, the reasons for installing coloured lighting are often related to reducing disturbance to animals that are sensitive to a certain part of the light spectrum, or purely for art or aesthetic reasons. For different kinds of animals, the sensitivity for different light types has been mapped. This resulted in special cyan-green lighting (Philips ClearSky), causing birds who first were attracted to platforms at sea, to now avoid human off shore activities and to not get lost due to magnetic disturbance (Poot, Ens, de Vries, Donners, Wernand & Marquenie, 2008). Similarly, there has been orange-red lighting (Philips ClearField) to decrease disturbance to bats, although certain amber lighting is being used for this purpose as well (Fure, 2012). Unfortunately, a solution that limits disturbance to multiple species at the same time is not available or known yet and seems impossible to accomplish. It does show that the needs of local animals determine the different ranges of light to be applied in the environments. However, with wildlife being different for various environments, this will further increase the the variety of light that car drivers are exposed to. These developments concern lighting specialists, as the use of differently coloured lighting will lead to significant visual changes in driving conditions, and there is currently very limited knowledge about the possible detrimental effects of transitions with coloured lighting on visibility and road safety.

1.1.2. Implementation issues

Local experience studies related to coloured road lighting have been conducted by Dutch cities and provinces, which are in the process of replacing existing luminaires on country roads with green LED lighting (Steg, De Waard, Lindenberg & Brookhuis, 2010; Provincie Gelderland, 2009, 2013). However, one can question the soundness of the reasoning and motives behind the studies and implementations. Gelderland province’s policy to install green lighting is motivated by green light’s higher luminous efficacy, resulting in lower energy consumption, but also a better fit of this coloured light to the human spectrum sensitivity at night, and preventing disturbance to nocturnal animals (Provincie Gelderland, 2009). However, for different animals this spectral sensitivity varies significantly, which is why there is special bat-friendly red-orange- (e.g. ClearField; Philips) and bird-friendly blue-green (e.g. ClearSky; Philips) LED lighting. One may thus wonder what animal the province had in mind when deciding to approve a green LED policy. Furthermore, humans are most

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1 The ratio between the luminous flux of a lamp (light output) and the power consumed in that lamp is termed as luminous efficacy in lumen per watt (i.e. how energy efficient the light is produced).
sensitive to bluish green (cyan) under low light (mesopic) conditions, whereas the ‘green’ lighting applied on roads often has red LEDs added to the spectrum. Red LEDs are added to increase colour perception (Innolumis, 2015) and thereby road sign recognisability. Also, the typical higher lumen per watt of green LED lighting is only beneficial at higher luminance levels, because human colour vision at mesopic (low luminance) conditions is limited (Lewis, 1999). It therefore seems as if the claimed benefits and reasons for application of green road lighting are not as strong and convincing as presented by the province.

Other questions are related to the purposes of these reports by Provincie Gelderland (2013), as expert groups like police and road maintenance authorities indicated that they preferred white over green lighting. This information was not used to reconsider the policy or to commence further investigations before implementation. In other research supported by a local government, residents were asked whether they liked the implemented green road lighting, felt safe under it, and whether they believe they may encounter negative consequences because of it (Steg et al., 2010). Perception studies reflecting on dynamic colour changes in lighting have been explored as well, but also by directly asking for stakeholder perspectives (Den Ouden, Keijzers, Szostek & De Vries, 2012). These subjective questions could be of additional value for an evaluation, but should not determine or assess the quality of a lighting implementation for future purposes. When visibility and observing dangerous objects and situations is the main reason for lighting to be applied in the first place, an objective measure must be used.

1.1.3. Unintended accidents

Unfortunately, there is not enough public data available to analyse the influence of currently used coloured lighting on roads. This type of lighting has not been in use long enough, and is often installed on relatively small sections of road. These sections of road thereby seem to be used as a sort of testing ground, but lack scientific research that supports reasons for implementation. Except from a few verbal reports about poor visibility after or during coloured lighting transitions, the possible detrimental effects of coloured lighting have received little attention. In fact, the occasional reports in the media show that local coloured lighting implementations are rarely followed by systematic investigations of their effect on safety, or even questioned by the media itself (Omroep Zeeland, 2015). This is surprising, considering examples in which it is known to have gone wrong before. For example, the regular white lighting was replaced with blue lighting in Amsterdam’s Vondelpark as part of an art’s project (Coevert, 2012). Due to the poor visibility, this lighting soon led to a significant increase in serious biking accidents, causing the original lighting to be quickly reinstalled after only two weeks. This is a good example of where the accessibility of the LED technology and a lack of professional implementation, contributed to an increasing variety in public lighting. Although this example only included a biking and pedestrian area, changes in light levels and colours may be a disturbance to all motorists, cyclists, pedestrians and residents (Van Bommel, 2015). Different light colours might require different intensities to create similar visibilities. It is generally known that drivers should not experience great changes in intensity level or uniformity during night-time driving, to keep an optimal and constant level of adaptation for mesopic (0.003 - 10 cd/m²) vision (Alferdinck, Hogervorst, Van Eijk, & Kusmierczyk, 2010). This emphasizes the need for gradual transitions when there are large differences in intensity between road sections that cannot be avoided or are otherwise to be expected (Deutsches Institut für Normung, 1981). There could also be a recommended maximum change in lighting classes when changing roadways (Gibbons et al., 2014). If not, different lighting could require adaptation, thereby impairing visibility and resulting in a driver that might be temporary travelling partially blind.
1.1.4. Regulation & Recommendations

Because there are currently no recommendations for coloured lighting and related transitions, it is unknown whether the general safety on roads is at stake. The problem is that lighting systems, no matter what colour, are currently measured on photometric measures like light levels, uniformity and glare restriction. Although these measures ensure that a similar light level is present with differently coloured lighting systems, they do not necessarily guarantee the same visibility. One of the reasons for this is that coloured LEDs are often small bandwidth light sources, meaning that they only emit light at a small specific bandwidth of the visible light spectrum. Under such conditions it is difficult to see all colours in the environment, because vision is based on reflected light. If a red object is shown under blue lighting, it will be impossible to see it is red because there is no red light that is reflected back at the eyes. A red traffic sign could thus be harder to detect and can only be seen on differences in luminance (i.e. luminance contrast). The experiment by Terry & Gibbons (2011) is an example in which participants were given object detection tasks for different coloured objects (red, green, blue and grey) to measure the distance at which they were visible. They found that the coloured targets required lower luminance contrast level than did the grey target. However, the impact of this colour contrast was very different for each colour, lamp type and luminance level. In some cases, it could therefore be even better to have no lighting installed rather than lighting with limited visibility, as this could create a false sense of confidence for a driver that does not know what he might be missing out on (Van den Broek, 2015). A better suggestion for the subjective or photometric measures would therefore be to base the lighting regulation or recommendations on measures of visual performance in detecting visual stimuli. These objective measures would allow for measuring basic driving tasks like detecting other drivers, signals, obstacles and road characteristics. After all, the primary purpose of lighting (outside urban areas) is to increase visibility during driving. It is therefore more important to measure and compare lighting on differences in visual performance, than on subjective measurements or fixed photometric requirements which could lead to significantly different results in visibility among a range of lighting installations.

1.1.5. Current study

Transitions between different types of (coloured) road lighting are relatively new, and the exact effect on drivers remains unknown. The purpose of this research is to determine empirically whether temporal colour transitions affect visual performance; more specifically, the detection of small, grey objects. With different temporal coloured light transitions at the same transition speed and luminance, object detection might seem to be determined by luminance and colour contrast only. However, there are multiple reasons to expect visibility in coloured lighting transitions to be determined by more than these two types of contrast. First of all, a fixed grey object can be lit up differently under different coloured lights. As the sensitivity to luminance changes over the spectrum, visibility could thus change as well. Secondly, although theoretically there should be no change in dark-light adaptation when only changing colour, there do exist large discrepancies in the perception of light intensity (brightness) between colours (Van Creveld, 1999). Object visibility differences could therefore indeed occur on a perceptual level when the luminance is the same. Thirdly, during low light conditions, foveal tasks are performed better in red light, whereas peripheral performance is better in blue (Várady et al., 2007). In real-life driving situations, foveal and periphery vision is used in combination for various tasks, but most road lighting is designed for foveal vision (ANSI/IESNA, as cited in Terry & Gibbons, 2011). Due to differences in spectral sensitivity to luminance, visibility will differ as well. Taken together, it is expected that when other variables (e.g. object colour, distance, luminance) are kept constant, there could still be a difference in performance after a transition into a different colour of light.
With the current experiment, it was investigated whether temporal colour transitions indeed affect object visibility, and to make an effort in determining whether future research or regulation is required on this topic. The main research question will explore whether there is an influence of transitions in coloured road lighting on the visibility of objects for car drivers, and whether some colours or transitions are worse for road lighting purposes compared to others. It will thereby help to better understand whether it is possible to guarantee safety on a similar level when existing photometric lighting requirements are applied on coloured road lighting. This is expressed in the following research question;

**Research question 1:**
What is the influence of temporal transitions in coloured road lighting on the visual performance of drivers in mesopic lighting conditions?

Secondly, some studies (Provincie Gelderland, 2013 & Steg et al., 2010) have taken subjective ratings of visibility as a measure to determine whether coloured lighting is acceptable for implementation. It should be assessed whether the value of subjective ratings for coloured road lighting implementation can be directly linked to performance measurements. The second research question should clarify the extent to which these ratings can predict the visibility for different types of coloured lighting;

**Research question 2:**
Are subjective ratings of object visibility a reliable predictor for visual detection performance?

An overview of related research is used to frame the area wherein this study operates. After this theoretical framework, the hypotheses will be presented and explained further.

### 1.2. Theoretical framework

Research directly related to the use of coloured light in road situations is rare, as it was not used in professional road applications until recently. However, multiple research fields offer relevant theory and practical context to design an experiment that can help answer questions around experiencing and working with coloured light.

#### 1.2.1. Human perception

From a human perspective, there are currently two theories on human colour vision that explain how different colours of light are perceived. Both these theories are combined in the *stage theory* (Fairchild, 2005). The first stage is the Young-Helmholtz Trichromatic theory that is based on the red (Long), green (Medium) and blue (Short) wavelength sensitive cones that are mostly located in the fovea of the eye (2° on-axis focus area). These signals are transformed in the brain's visual cortex into a second stage, which is described based on Hering's Opponent-Colour theory. Here, red-green, yellow-blue and light-dark physiological responses are measured and depend on input from the first stage (Krauskopf, Williams & Heeley 1982). These second stage ‘cardinal-axes’ are opponent within their couple, which means there is either a red or green, and a yellow or blue stimulation, not both (Hurvich, 1957) (Figure 1). After all, there is no such thing as a red-greenish or

![Figure 1. Stage Theory](image-url)
yellow-bluish colour. Thus, when adapted to a bright red colour, sensitivity should decrease over time for red but increase for green (Hurvich & Jameson, 1957).

The adaptation to colour is complex to research, due to this stage theory. It is not exactly known on which stage the colour adaptation is more prominent. However, adaptation is generally assumed to occur on both stages (Fairchild & Reniff, 1995). For the second stage, Hurvich and Jameson (1957) found that after adaptation to a red light, sensitivity on the red-green cardinal axis dropped significantly for red, while sensitivity for green did not. This chromatic adaptation can be divided in two mechanisms; a fast neural mechanism with a 40-70ms half-life time and a slower one with a 20s half-life time. This leads to a full colour adaptation after two minutes, but because the largest part of adaptation happens almost instantly, the maximum time required for a 98% chromatic adaptation at constant luminance is approximately reached after one and a half minute (Rinner, 2000; Fairchild, 2005). This is applicable to every colour, and is different from adaptation to light intensities.

In contrast to the adaptation to colour, light intensity adapts using a pigment bleaching mechanism. This mechanism mainly controls the light-dark adaptation with the amount of pigment. Less pigment means weaker responses at high light levels and thus no overstimulation. Dark-light adaptation happens within seconds, but the reverse can take up to 30 minutes (Fairchild, 2005) and is mainly due to regeneration of the pigment. In light levels from full darkness up to 0.003 cd/m², human vision is in the scotopic state in which only the light sensitive rods are active. From approximately 10 cd/m² and upwards it is in the photopic state in which the cones are active. The range in the middle, the mesopic state, uses a combination of both rods and cones depending on the light level (Alferdinck, Hogervorst, Van Eijk, & Kusmierczyk, 2010). When transitioning from higher to lower light levels, the rods become more important and spectral sensitivity model \( V(\lambda) \) moves towards shorter wavelengths \( V'(\lambda) \), this is called the ‘Purkinje’ shift. Lighting that is optimised for vision in these conditions therefore has a relatively high S/P-ratio (Scotopic/Photopic), which means the light distribution contains more blue. This is more effective at the periphery of the focus area, as the short wavelength sensitive cones (blue) are located on the periphery of the fovea.

1.2.2. Visibility

From a lighting technology perspective, research by Boyce (2008), Bullough and Rea (2000) and others found that reaction time (RT) increased when going from photopic to the scotopic state for different types of lighting. For example, between conventional High Pressure Sodium and Metal Halide lamps, differences in visual performance were almost only observed in low light level and off-axis situations (i.e. deviation from line of focus, periphery). The positive difference for MH lamps was probably due to the high S/P-ratio of the lamp (i.e. presence of the blue spectrum). It therefore benefits more from the Purkinje shift and is more effective for side-line, border and movement recognition instead of fine acuity tasks (i.e. reading signs or facial recognition). Unfortunately, the human lens slowly turns yellowish with age and thereby decreases the amount of blue light from entering the eye (up to 25% for 80-year-olds). This makes light sources with blue in the spectrum less effective for elderly (Alferdinck et al., 2010). It is therefore possible that they prefer yellowish HPS lighting over white bluish LED’s with high colour temperatures (e.g. 5000K).

Another factor in the perception of the surrounding environment is the colour rendering or rendition index (CRI). This index represents the accuracy in which the colours of an object or human appear under a light source compared to a reference type of light with the same colour temperature. Although research on this subject contradicts each other on whether a higher CRI does increase facial recognition
for road lighting (Knight, 2010) or not (Lin & Fotios, 2013), there is consensus about it increasing colour discrimination and perception of comfort. Generally, the better the distribution of the spectrum is (continuous), the higher the CRI is. Strong monochromatic light sources (i.e. small bandwidth) such as Low Pressure Sodium lamps or small bandwidth coloured LEDs, should therefore lead to lower visibility on a busy city road on which many different coloured objects are present. This does not necessarily mean that safety is automatically reduced with lower colour discrimination, as research has also shown that colour deficiencies do not necessarily increase risk in road situations (De Jong, 1995; Boogaard & Vos, 1989 as cited in Schreuder, 2008). Outside typical city roads, such as on highways, the lack of optimal colour vision seems to have barely any consequences. Although people can be hesitant when new strongly coloured LED lighting is applied, current low-pressure sodium lighting has similar monochromatic characteristics and is used and accepted in many outdoor road situations today (Schreuder, 2008).

1.2.3. Models of measurement

Heterochromatic brightness matching (HCBM) is a method often used for measurements in mesopic conditions. It is a subjective measurement for comparing light sources, and therefore has multiple problems and limitations related to accuracy. Measuring the extent to which people can detect objects during actual driving tasks is more relevant, exact and representative than brightness matching (Várady, 2007). Due to the European MOVE programme, two new models were developed for mesopic photometry. One practical model is for fairly broad spectral power distributions, and a second more complex model for chromatic task performance (Eloholma, 2005). Unfortunately, these models describe the theoretical visual response, but do not predict practical visual performance while driving at night. For drivers, priority is on whether there is an object present that if undetected could lead to potentially dangerous situations. A driver should thus be able to simply perceive a visual stimulus, without necessarily being able to perceive colour or detail. The fundamental visual driving tasks used for the MOVE model, are therefore based on: “Can an object be seen”, “How quickly” and “What is it?” (Eloholma & Halonen, 2006). These questions could be measured more objectively, by transforming them into detection thresholds, response times and correct identifications. This allows them to be compared under different circumstances, free of subjective interpretations and beliefs. Alferdinck (2006) confirms that response time is more realistic as a performance task when driving a vehicle, and that it describes data for mesopic luminance better than the photopic model currently used in photometry.

In public lighting, there are standards for visibility that are often used to compare lighting systems. For pedestrian areas, facial recognition is often involved in the requirements to increase feelings of safety. For driving situations facial recognition is less relevant, but objects on the road are important to avoid. This is why the Small Target Visibility (STV)-method is used for road lighting instead (IES, ANSI/IESNA 2000, 2014). Van Bommel (2015) indicates that the Small Target Visibility model for visual performance is a design metric for good-quality road lighting installations. An 18 by 18 cm flat and square aluminium plate with a diffuse reflectance factor of 0.20 is used for these calculations of visibility (Van Bommel, 2015). This standard sometimes leads to disagreement about its suitability for all driving visibility related tasks. Real-life objects could range from inconspicuous lost cargo or glass on a road, to mice or deer sized animals or even humans with reflecting raincoats. Despite these debates, staying as close to this standard as possible would make measurements better to compare with other findings, as these real-life objects could differ enormously in their visibility.
To make comparisons between different situations in which the STV is applied, the visibility level (VL) can be calculated with Adrian’s model (Adrian, 1989). This model is used to determine the quality of a lighting system, where the VL is considered to be a common and relevant index for visibility on a road (Mayeur, Bremond, Bastien, 2010). It is based on contrast, but takes factors like age, exposure time, and positive/negative contrast into consideration as well. To create a similar VL for objects in different situations, it is effective to increase the luminance difference between the object and the background, by changing the general luminance, the position, the colour, or the object- background reflection factor (Narisada, 1992). By determining a VL, values between 1 and 10 can be thought of as being “undetectable” and “detected by everyone”. The middle of this range should be around threshold level. Values higher than 5.5 are thus needed to guarantee detection by the majority of people (Mayeur, Bremond, Bastien, 2010). According to Adrian (1987), a visibility level of 6 marks the border where safe driving is just possible for people with a visual acuity that is close to the minimum values set by law.

If the response times of braking for objects would be considered to be an acceptable measure for visual performance in road situations, it is hard to determine a maximum allowed increase between different types of (coloured) lighting. There probably is considerable variability due to factors such as the braking ability of a car. The response time varies also between optimal daytime (photopic) conditions and low light (mesopic) conditions while driving at night (Crundall, Chapman, Phelps & Underwood, 2003). Furthermore, there are factors like the visual reaction time, processing to muscle response, pedal response, mechanical brake action and braking distance to a full stop. However, when taking the minimum braking distance regulations set by law as a fixed reference point, there is the possibility to calculate the influence of a certain additional response time on the total stopping distance when the speed is known. What is seen as an acceptable increase in response time due to coloured road lighting, will thus be subjective, context dependent and up for debate.

1.2.4. Night-time driving

Road lighting can be applied for traffic, personal or social safety, visual guidance, comfort or decoration. The calculations to create an optimal and balanced situation for a crossing can get very complex. However, the main design considerations for roads are generally based on (NSVV, 2011);

- a high uniformity of the lighting to make contrasts clearly visible, and improve comfort by avoiding a flickering zebra effect on the road.
- a fixed amount of luminance depending on the road specifications and requirements (location, width, speed, intensity, users, etc.).
- a minimum amount of discomfort or disability glare from the mounted luminaires, which could blind drivers.

To make sure these values meet minimum requirements to guarantee safety, most countries have lighting guidelines that are derived from recommendations set by the International Commission on Illumination (CIE). The widely accepted recommendations for photometric requirements are categorized in different lighting classes, depending on the situation at place (NSVV, 2011; CIE, 2010). These lighting classes have only been tested for the regular white or amber lighting that has been in use for many years. During installation of coloured lighting, the assumptions are that these values should be at a similar level to create similar visibility. However, Alferdinck (2006) conducted a study in a driving simulator in which under mesopic light levels targets were presented. For different background luminances between 0.01 and 10 cd/m², the background colour varied between white, yellow, red or blue, while driving at different speeds and with different object eccentricities. They measured the RT,
missed targets and driving behaviour. Their observations were that detection performance in general decreased with decreasing luminance and increasing eccentricities up to 15 degrees. Performance in these conditions was worse for red than for other colours, which was also found in other research in a driving context (Bullough and Rea, 2000; Akashi and Rea, 2002; Lingard and Rea, 2002). In these periphery conditions, this can be explained with the (Purkinje) shift of human eye sensitivity towards blue under mesopic conditions. Other observations were that speed further increased driving errors and resulted in a higher steering effort. This could be the result of narrower fixation points, like a type of tunnel vision, as described by Rogé et al. (2004).

The visual performance in these mesopic night-time driving conditions is further elaborated on by Eloholma, Ketomäki, Orreveläinen and Halonen (2006). Based on the performance measurement implementation for mesopic conditions, they tested performance under different luminances with difference stimuli colours (LEDs) on a white background. The five stimuli colours used in these measurements were: blue, cyan, green, amber, and red. They found that the mean response times of braking for objects were not very different at high luminance levels. This implies that when the contrast is high enough, there is no difference in response times between stimulus colours. At lower luminance levels, the response times increased for all colours, likely because target visibility reduces around threshold levels. Due to their focus on peripheral vision, they found that blue had a performance advantage over red with shorter response times and lower deviations. Comparing this to the spectral luminous efficiency function for photopic conditions V(λ), this function underestimated the relative sensitivity change towards shorter wavelengths (Purkinje shift), and overestimates the longer wavelength sensitivity in mesopic conditions. They claim luminance contrast between target and background is a better indicator for predicting the visibility of chromatic light sources at mesopic light levels, for peripheral vision. However, adaptation variations due to transitions or fast involuntary movements (i.e. saccades, up to 0.04 seconds) were not measured in this experiment (Van den Brink, 2010; Van Bommel, 2015). Moreover, neither were other secondary foveal tasks nor distractions included, because these are all extremely hard to control and will never represent all traffic situations. Furthermore, luminaires, commercial lighting and car headlights can create situations in the photopic range, while areas on the side, unlit roads and the sky are in the scotopic range. Installing road lighting and aiming for constant mesopic conditions is therefore complicated. All the visual tasks combined in driving need not only foveal, but peripheral vision as well (Eloholma & Halonen, 2006). In other words, there is no realistic method for repetitive realistic measurements in experiments. No single method will fully grasp the difficulty and complexity of visual tasks during driving at night (CIE, 1992). With all real-life variables, it is nearly impossible to come up with an accurate and practical adaptation model. Therefore, for now and by approximation, the average global light level (total visual field) is a good indication for adaptation level when taking glare and eye movement into consideration (Irawan, Ferwerda, & Marschner, 2005).

1.2.5. Chromaticity & Brightness

Parallel to road lighting and driving research, task performances such as with Schnellen charts, have been measured in different coloured light. The results for multiple experiments indicated that there was either a positive difference for red, or equality in performance for red or green lights. Blue light was inferior, even though subjective assessments showed people clearly preferred the blue light (Van Creveld, 1999). Although objective performance and subjective preference measures are both related to the perceived amount of light, they did not match. The reason for this effect is unclear. Between different light colours the effect could be caused by the inconsistency between the perception of brightness and the actual luminance in differently coloured lighting. These discrepancies are quite large
and could cause lighting measurement equipment to appear inaccurate when not correcting for measuring highly saturated coloured light. This effect is called the Helmholtz-Kohlrausch effect (Wyszecki & Stiles, 1982). It describes how saturated coloured stimuli are often perceived as brighter compared to a white stimulus of equal luminance. Even for white light, high correlated colour temperatures (CCTs) look brighter than low CCTs (Viénot, Durand & Mahler, 2009). As discrepancies in luminance for equally assessed brightnesses of up to 9:1 have been reported for different spectra (Van Creveld, 1999), visibility could depend on or be partially influenced by this effect.

According to Corney (2009), another phenomenon of Helmholtz-Kohlrausch effect is that some colours (red, blue) might naturally appear brighter compared to others at the same luminance. Also a higher saturation could make a colour appear brighter. These effects could play an important role in the perception of coloured road lighting, as some light might require a higher luminance to appear similarly bright as another (Van Creveld, 1999). However, if changes in luminance are applied in road lighting to make different road sections equally bright, there could be more actual variety in light level. This changing light level then requires more adaptation, which could again negatively influence visual performance (Van Bommel, 2015).

1.3. Practical implications of theory

From the different perspectives in this theoretical framework, there are multiple points of interest that are especially relevant for giving shape to an experiment around the research questions. According to literature, there are four colours that from a human perspective are the main contributors in colour perception, because they are part of the stage theory (i.e. yellow, blue, red, and green). Differences in the distribution of the L, M, and S cones on the retina are thereby predicting different performances and lower the expectations on visual performance for some of these colours (e.g. blue for foveal vision). For transitions between these different colours, the maximum amount of time that is required to get an almost complete chromatic adaptation is specified at approximately one and a half minute. The extent to which the directions or the combinations of the colours in the light transitions play a role remains unclear, however.

For the experimental setup, the MOVE project (Eloholma, 2005) showed an interesting objective measurement approach which should give more reliable results compared to previous subjective methods (e.g. HCBM). The focus on how quickly people perceive the same object in different lighting is thereby providing results with a higher reliability than before. With the small target visibility method, this measurement could be accurately replicated for multiple times, and be compared with other research using the same methodology. Equal visibility levels thereby guarantee similar visual conditions in different coloured light transitions or object positions. The colour rendering index, however, plays a limited role on the colourless, grey object that was used. This CRI is poor for all small bandwidth lighting in comparison to full spectrum white light, and therefore has limited value in object detection experiments in coloured light. To give the coloured light conditions in an experiment similar lighting values (e.g. luminance levels) as in real-life, the lighting can be based on (inter)national guidelines, for example as set by the CIE (2010). However, because the perception of brightness changes for different colours (i.e. the Helmholtz-Kohlrausch effect), the visibility of objects could still be different in similar lighting conditions as well. Janoff (1989) claimed that subjective ratings of visibility can be directly linked to objective measures of visibility for regular white light. However, white light is perceived daily and therefore leads to constant practice and experience with situation assessment. Whether this link holds for coloured lighting as well is therefore not known yet.
To avoid a great variety in experimental factors, such as changing spectral luminous efficiencies for different luminance levels, the amount of conditions needs to be limited to create a balance between realism and experimental control. Varying disturbing environmental factors could therefore be limited with an indoor setup, although previous experiments showed that realistic, outdoor experiments with high environmental validity (Terry & Gibbons, 2011) could give great insight in varying driving relevant factors too, although with limited significant conclusions. The use of comparable variables and measuring methods as used in other experiments (e.g. similar light levels), could make the results of the experiment easier to compare and increase the value to the road lighting research community.

1.4. Experiment hypotheses

Almost all research mentioned has related aspects with the main problem of coloured light in mesopic lighting conditions while driving. However, none of it focusses on transitions with coloured light and the impact it may have on visual performance. With an increasing chance of encountering these situations, combining existing knowledge in these areas is no longer enough to use as a basis for realistic expectations and recommendations for coloured road lighting implementations. This study will therefore be conducted to fill this gap and get more insights in the effects of this specific (future) road lighting on visibility. From a fundamental or theoretical perspective, it would perhaps be most relevant to see which colour transitions are expected to cause the largest effect in visual performance and to test these against empirical observations. In contrast, for practical applications it would be more relevant to consider colours that are currently implemented in real-life situations. In this experiment, only the colours encountered in real-life functional road lighting (as mentioned in section 1.1.1) will be used to answer the research questions. As theory does not explicitly state how adaptation varies in time between different colours of light, the hypotheses are based on the assumption that larger distances in colour space lead to a larger required adaptation.

Research question 1:
What is the influence of temporal transitions in coloured road lighting on the visual performance of drivers in mesopic lighting conditions?

Based on this research question and the work in the field of light and human perception, the following hypotheses are put forward:

Hypothesis 1:
Response times will be longer from/to coloured light transitions compared to standard white-white transitions.

White-to-white transitions do not require chromatic or light-dark adaptation when the luminance is constant. It therefore represents the standard lighting situations currently encountered, and will act as baseline for comparison with other transitions. Small bandwidth (i.e. coloured) lighting is expected to need extra adaptation time compared to white lighting, and thus requires more time to detect an object.

Hypothesis 2:
Response times will be longer in the white-to-coloured light transition than reverse.

This expectation is based on the fact that the visual system has to adapt from full spectrum light (all cones a little stimulated) to single cone (over)stimulation, which could reduce the sensitivity and
increase adaptation time for those cones. Of course, cones that are not stimulated by the coloured light keep their sensitivity and will adapt faster to stimulation.

**Hypothesis 3:**
Transitions with blue light will cause on average the longest response times in all colour-white (or reverse) light transitions.

Theoretically, at lower luminance levels, blue has the advantage over all other colours and thus is expected to lead to shorter reaction times (Eloholma et al., 2006). The eye is more sensitive to blue light in the periphery of vision due to the Purkinje shift (higher S/P-ratio). However, in the present experiments the effects of colour transitions on foveal vision will be tested. Some features of interest while driving a car that are normally falling on the periphery are therefore not tested. In the current experimental setup, blue will thus not have an advantage. Instead, red lighting should result in better performance for on-axis tasks.

**Hypothesis 4:**
A special transition between opposites in the visible spectrum (blue and red) is expected to have a larger detrimental effect on visual performance than other experimental colour-white transitions.

Blue and red are on different axes in the second level of the opponent vision theory (Fairchild, 2005) and two extremes in the visible spectrum (Eloholma et al., 2006). Thresholds for detection of chromatic differences are lowest for the colour the observer is already adapted to, and higher if the colour is further away in colour space (Krauskopf & Gegenfurtner, 1992; Shapiro & Zaidi, 1992 in Rinner, & Gegenfurtner 2000). This extreme colour transition therefore theoretically requires the largest adaptation and thus longer response times.

**Hypothesis 5:**
A higher luminance level will improve the visual performance in coloured light, leading to shorter response times.

In lower, scotopic light level conditions, the rods (black/white) are the primary input for vision. Colour vision with cones is best at photopic light levels. The ratio of rod or cone input depends on the amount of light. In supra-threshold, higher intensity light conditions, a larger ratio of cones provides better colour vision. Unless overstimulated, this should increase the visual performance. It is therefore expected that the higher light level leads to shorter response times.

The second main question related to the performance in coloured road lighting is about the comparison between the measures. Hypothesis six expresses the expectations related to this question.

**Research question 2:**
Are subjective ratings of object visibility a reliable predictor for visual detection performance?

**Hypothesis 6:**
Subjective ratings of object visibility do not correspond accurately to response time performance measures in coloured light.
Janoff (1989), argues that luminance contrast has a much larger effect on visibility compared to light level, especially under low light conditions. He also states that there is a direct link between visibility level and the subjective rating of visibility. In other words, Janoff argues that people can accurately judge the visibility of objects, and thus that such subjective evaluations should correlate strongly with performance on more objective reaction-time based visibility tasks. Although colour was never a factor in Janoff’s (1989) research, it theoretically should not influence luminance contrast (and thus visibility). Janoff and Havard (1997) did experiments with this for different spectrum lighting (HPS, MHN, MHS). Unfortunately, this was not LED lighting and the differences between these light sources were not nearly as large as the coloured LEDs used in this study. In current experiment, the Helmholtz-Kohlrausch effect could cause the perceived visibility of objects in different light colours to be different, even though they have the same visibility level. Subjective ratings could thus be influenced by these differences in perception of coloured light, thereby losing the direct link with performance measures. Another possible difference is that people have lifelong experience with different types of white light and the interaction with objects, which is not the case for coloured light. The known interaction between subjective judgement and actual performance for other types of light is therefore not known to them. Other factors of influence could be that people choose the colour in which they have best acuity or perceive as the brightest light (see section 1.2.5). It is therefore expected that subjective ratings do not directly correspond to response times under coloured lighting.
2. Method

2.1. Design

The main goal of this research was to investigate the differences in performance of road users in temporal transitions of coloured lighting, under mesopic lighting conditions. Existing models for photopic adaptation of vision did for a long time not predict night-time mesopic conditions well, and thus were quite meaningless in optimising vision for road users at night. Fortunately, efforts by Eloholma (2005) gave insight on adaptation of vision in mesopic conditions. Although this MOVE-model describes mesopic adaptation very well, it is the underlying method of objective performance measurement that is a useful approach for this experiment. The model describes that Can it be seen? How quickly? and What is it? are the three fundamental questions to make performance measurable in different situations. Translating to actual measures, this resulted in a detection threshold, a response time, and target recognition and identification (Eloholma et al., 2005; Halonen & Puolakka, 2010). For this experiment, all measures were suprathreshold (i.e. above minimal level to be detected) so they were theoretically always visible. The focus was on measuring response time (i.e. How quickly?) for object detection, to be able to compare the differences between temporal coloured light transitions.

To test the different coloured light transitions, this study used a scale model (Figure 4) that provided a good balance between the high experimental control and low environmental validity of a laboratory setup, and lower control and high environmental validity of a real driving situation. A previous trial experiment proved that this scale model method yielded similar results as a natural and realistic outdoor experiment. The experiment had a 12 (colour transition) x 2 (luminance level) within-subject design with response times and subjective ratings as the dependent variables. Four coloured light transitions were considered; red, green, blue or amber. These colours all had a transition from and to white, and were based on the two cardinal colour axes (see section 2.3.2). A single white-white transition was added as control condition. Also a red-to-blue transition was added, which as two colours on different opponent axes in the human visual system, could provide larger effects compared the other, more conventional road lighting transitions to white. An overview of all transitions is shown in Error! Reference source not found.. Based on scenarios that represent real-life coloured lighting situations, the luminance was set for mesopic conditions at either 1 cd/m² or 0.15 cd/m² at the participant’s position. This gave a total of 24 transitions in the experiment. Participants had to detect objects on the model road, which were positioned between luminaire A at 4-meter distance (80m in real-life) and luminaire B at 1.15 meter (23m) further (Figure 4). The difference in distance of the object positions was not more than 10-15 cm. Participants were wearing a pair of glasses with coloured LEDs attached, and mechanical shutters in front of the glasses. Once they were wearing the glasses with shutters closed, they were adapted for 90 seconds to one of the adaptation light colours (as explained in section 1.2.1). When the glasses flipped open and the road was visible, the response time was measured until a braking responses on the pedals was registered. Immediately after their braking response, participants had to verbally rate the visibility of the object standing on the road. As participants knew they had to rate the object, this increased the chance of them actually wanting to

<table>
<thead>
<tr>
<th>White</th>
<th>To</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>To</td>
<td>White</td>
</tr>
<tr>
<td>White</td>
<td>To</td>
<td>Green</td>
</tr>
<tr>
<td>Green</td>
<td>To</td>
<td>White</td>
</tr>
<tr>
<td>White</td>
<td>To</td>
<td>Blue</td>
</tr>
<tr>
<td>Blue</td>
<td>To</td>
<td>Red</td>
</tr>
<tr>
<td>Red</td>
<td>To</td>
<td>Blue</td>
</tr>
<tr>
<td>Blue</td>
<td>To</td>
<td>White</td>
</tr>
<tr>
<td>White</td>
<td>To</td>
<td>Amber</td>
</tr>
<tr>
<td>Amber</td>
<td>To</td>
<td>White</td>
</tr>
<tr>
<td>White</td>
<td>To</td>
<td>White</td>
</tr>
</tbody>
</table>

Figure 2. Experimental transitions

Different orders presented at both light levels.
see the object first before responding. The experiment was counterbalanced by switching the order of the transition series by both light level and by the order of colour transitions within each light level. In total four different stimuli orders were created, with each order being performed by an equal amount of participants. In each order the participants were exposed to 24 transitions. The ending colour of the last transition was used as adaptation colour for the next transition, to limit the required number times to change colour. The total time taken by a single experimental session was approximately 50 minutes.

2.2. Participants

Participants were recruited with convenience and availability sampling and consisted of colleagues at Philips and students of Eindhoven University of Technology, the Netherlands. As there was no previous experiment on which the sample size could be based, an estimate was calculated based on an expected moderate effect for the main comparison of colour transitions on response times. For this main effect at least 19 participants were needed. Eventually 27 colleague and student participants participated in the experiment. In this sample, 16 were male (59%) and 11 were female (41%). The mean age was 26.48 years (SD = 2.59; range 23-31 years) and 11 of them wore lenses or glasses (41%). They were automatically spread out equally over one of four conditions, without their knowledge, based on systematically filling the conditions by the order in which participants came by. Of all 27 participants, one participant’s response times were lost due to experimental software errors. The subjective ratings, however, were recovered and used where applicable. Another participant’s data was completely removed from the sample due to very poor eyesight, which did not meet the experiment requirements. Therefore, data analysis was performed on the remaining 25 participants of which 14 were male (56%) and 11 were female (44%).

Participants were not required to have a driver’s license, due to the main focus on the response time instead of a real driving simulation. They were qualified to participate in the study if they were between the age of 18 and 40 years old and had no degraded vision or known eye defects. The 40-year limit was set, as quality of vision generally goes down after 40 years of age (American Optometric Association, n.d.). However, in general near (myopia) - and farsightedness (hyperopia), lack of lens flexibility (presbyopia), colour blindness and cataracts (clouded vision) are a few of other most common problems. These defects could have very different influences on vision and were therefore excluded in this study. Corrected acuity with glasses or lenses was allowed. As a result of these criteria, the sample of participants was not a fully representative sample for all road users. For this experiment, the focus was on a homogeneous sub sample of the population that had the smallest chance of visual limitations. This age group also covered the largest part of people traveling the most by car (CBS, 2014). If a significant effect was found within this group, further research could focus on one of the many specific groups with deviations from regular vision that are also allowed to participate in traffic.

Before the start of the experiment, each participant was shortly tested on their quality of vision. This was done with an acuity test and a colour blindness test. The acuity test was done with a Schnellen chart, often used by ophthalmologists. Larger than 1.0 is above, and below 1.0 is a below average visual acuity. Participants were required to have a minimum of 0.8 visual acuity score, to limit the experiment to road users with regular quality of vision. Dutch law allows for acuities as low as 0.5 visual acuity to obtain a driver’s license (CBR, 2015). This test does not give any information about visual capabilities at night or eye defects. It also does not guarantee good contrast sensitivities to see depth (Heiting, 2014).

The colour blindness of participants was measured with an Ishihara pseudo-isochromatic plates test. Each plate consists of coloured dots that form a number inside the dots of another colour, and mostly
consists of a variety of green/bluish and red/orange tones. People had to recognise and speak out the number on each plate. The red-green deficiency (deuteranopia/deuteranomaly) that is detected with this test is by far the most common colour deficiency (Hunt & Pointer, 2011). After completion, participants could continue with the main part of the experiment. They were not compensated for their participation.

2.3. Manipulation

2.3.1. Experiment scenarios

The model road that was used for the experiment was comparable to real-life situations. Current roads that have coloured lighting were hereby of guidance. To recreate situations in which different mesopic conditions determine the visibility, two realistic and typical scenarios had been created. Plainis and Murray (2002) have suggested that there was a link between RTs and driving performance, because road accidents increase at low light levels, reduce visibility, and cause longer RTs. For this reason, there were two type of roads based on current photometric (light level) recommendations, used to create scenarios for measuring participant performance. Factors that were not taken into account were atmospheric and road conditions, car lights and windows, trees and other obstructing objects, specific ambient lighting, luminaire age and maintenance, and other factors that were not specifically mentioned in these scenarios. These factors fluctuate too much in different driving situations.

**Scenario 1: Central city road**

A central, two lane main road has a single-sided lighting arrangement with luminaires every 23 meters, at a mounting height of 6 meters. The traffic composition is motorised only, with a high traffic volume. There are separated biking lanes and separated parking options on the sides. There is no lane separation for cars and the maximum speed is moderate with 50 km/h. Furthermore, the intersection density is relatively high and there is quite some other ambient luminance. The visual guidance is good, but there is a higher complexity in the visual field due to surrounding buildings and activities.

According to lighting classes set up by the International Commission on Illumination (CIE, 2010), these parameters give the above situation a rating of a M3 road lighting class, and puts it in the upper-middle range of the mesopic lighting conditions, typical for night-time driving conditions (Plainis, Murray & Charman, 2005). This leads to surface luminance requirements as shown in Table 1.

**Scenario 2: Residential neighbourhood**

A local suburban road with a single-sided lighting conditions at a mounting height of 6 meters every 23 meters. The traffic composition is mixed with bikes and pedestrians and has a low traffic volume. The parked vehicles are present on the road and there is no lane separation. There is a 50 km/h speed limit and a low amount of intersections. The disturbing ambient luminance is moderate with a moderate visual guidance. There are no special requirements for additional facial recognition (optional in residential areas).

According to CIE (2010), this gives the above situation a rating of a P3 road lighting class. This is more in the lower-middle range of mesopic lighting conditions. Both these scenarios transformed into a road lighting setup with CalcuLux, gave the required values as in Table 1. The coloured light transitions in the experiment were tested on both light levels.
According to Plainis et al. (2005), night-time driving is mainly in these mid- and high mesopic values. Other research related to visual performance during night-time driving, for instance by the MOVE consortium, also used these values during their study (Eloholma, 2005; Eloholma & Halonen, 2006). The values used in this experiment were based on the road lighting recommendations of the CIE (2010), which in this case were similar to the Dutch recommendations as can be found in the Recommendations for Public Lighting (NSVV, 2011).

2.3.2. Coloured LED lighting

From theory on human perception it could be expected that the largest effects should be measured at the second stage of human colour vision. In this opponent colour theory, main colours along the cardinal axes in the human visual cortex (i.e. red-green and blue-yellow) should give the largest differences in visual performance, and have therefore been used in other adaptation related research as well (Rinner & Gegenfurtner, 2000; Eloholma et al., 2006). As the focus in the experiment was on exploring whether the effects of visual performance changes visibility in practical situations, currently used coloured LED lighting close to these cardinal colour opponents was used. The experiment mainly had transitions between colours and white, as this was the most likely transition to encounter in real road situations. There was only one experimental transition between two colours. The hues used on the road lighting examples found around Eindhoven correspond well to the primary hues on these cardinal axes. The relatively new outdoor coloured lighting systems found in road applications in and around Eindhoven were orange-red, golden green (i.e. green with some red) and blue (cyan). They were measured with a JETI Specbos 1211 spectro-radiometer. Amber was used to recreate the Low Pressure Sodium lighting still found outdoors as well. Although other studies assess with actual sodium gas-discharge lamps, this study used LEDs with the exact same frequency as coloured lighting. It does not guarantee comparability on all aspects.

The specific light distributions of the lighting systems were analysed and matched with a type of LED for use in the experimental setup. The Lumiled Luxeon Rebel Color series was selected based on their similarity in spectrum and ability to recreate the lighting scenarios. The specific LED types are found in Appendix A. As an exception to the other colours that were used in the experiment, the green light was combined with the orange-red LED to recreate the green that was found outdoors. This colour combination is often used to improve vision and colour distinction, and in this case recreated the Golden Green luminaires from the company Innolumis. This lighting was applied on the Velddoornweg in Eindhoven, the Netherlands. The spectrum of the LEDs was matched with the actual luminaire measured on the road, and it was assumed that the spatial light pattern on the model road was similar for the different colour LEDs. The individual LEDs were small bandwidth light sources, meaning that they only emit light at a specific bandwidth. This is in strong contrast with conventional High Pressure Sodium, Metal Halide or Xenon lamps for example, which emit (some) light everywhere in the spectrum. An overview of the type of LEDs used and their specific spectrum, can be found in appendices B and C.

### Table 1. Lighting values based on recommendations for scenarios.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Class</th>
<th>E_{h,pole} in lux</th>
<th>L_{avg, observer} in cd/m²</th>
<th>U_{overall}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>M3 class</td>
<td>53.0</td>
<td>1.00</td>
<td>0.40</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>P3 class</td>
<td>7.80</td>
<td>0.15</td>
<td>0.20</td>
</tr>
</tbody>
</table>

*Note:* Based on Calculux calculations, after NSVV (2011) and CIE (2010) recommendations.
2.3.3. Object detection model

The objects used in the experiment were based on the Small Target Visibility model. In this model it was defined that the object is a square of 18x18 centimeters, which on a 1:20 scale corresponds to 9x9 millimeters. The small square was grey and has a reflectance factor of 0.2. The height from which the object was normally observed was thereby scaled down from 1.45 meter to 7.25 centimeters. Furthermore, the objects were also varied in location. The place of objects during the experiment was changed and transitions without an object were introduced, to increase the element of surprise and minimise anticipation from participants.

The location of these objects on the road is of special concern with road lighting luminaires, as spacing between these luminaire poles prevents perfect uniformity of light on the road surface. The position at which an object gets placed relative to a luminaire, can determine whether it can be seen in positive (object is lighter than its background) or negative contrast (object is darker than its background). In regular road situations, luminance contrast is measured with differences in light level (i.e. dark-light situations), in which colour plays no role. Normally, the luminance contrast can be measured with the following formula, in which \( L \) is the luminance, and the resulting contrast values can be either positive or negative (Van Bommel, 2015; Eloholma et al., 2006);

\[
\frac{L(\text{object}) - L(\text{background})}{L(\text{background})}
\]

Although the experiment was set up on how (coloured) lighting is currently implemented (i.e. based on photometric measures), perceived contrast could be influenced by coloured lighting. The influence of this coloured light was therefore expected to add an additional factor to object visibility (see section 1.1.5).

Besides contrast, the distance and the side of the road on which the object was positioned could influence the visibility significantly due to differences in object illumination. To avoid differences in illumination at the location at which objects were positioned, these locations were selected based on measurements with a luminance camera (Figure 3).

![Figure 3. Luminance measurements](image)

*Figure 3. Luminance measurements*

*Luminance measurements to calculate equal visibility levels for objects, in different coloured lighting.*

The Adrian model (Adrian, 1989), as part of the Small Target Visibility model, was used to calculate comparable visibility conditions for each object on different locations in the different lighting conditions. The location where the objects were placed on the road was different for each individual light colour to keep the visibility level of the objects constant. More details about the calculations can be found in Adrian’s paper (1989). For this experiment, a constant visibility level of 7 was chosen for
all objects, to keep conditions comparable for all light transitions. This does not mean the luminances were necessarily equal too. The measured luminances for each object and background with their related visibility level in the different transitions can be found in Table 11 in Appendix B. These set visibility levels were suprathreshold and should theoretically be detected relatively well for all people with regular vision in white light. Visibility levels below 6 are not considered to be safe for driving with bad visual acuity (Adrian, 1987). To keep the visibility level constant in the different coloured light conditions, small differences in position and distance of the objects were necessary. The few centimeters difference in distances were negligible on visibility from the participant’s perspective, as this was mainly determined by the visibility level.

2.4. Setting and apparatus

The experiment took place in a large windowless dark space at Philips in which no light could penetrate. The 1:20 scale model was mounted on a platform that was hanging on electronic winches so that it was adjustable in height. The participants were seated on a slightly lifted platform, with electronic pedals in front of them. By means of a chin rest, their eyes were set 7.25 centimetres centred above the road of the scale model, which corresponds to the height of 1.45 meter in a normal vehicle (ANSI/IESNA, 2000). They could see the road in front of them, with a green roadside and buildings in the far distance. On the left side of the road, two small luminaires were mounted four meters away at 115 centimetres apart, which corresponded to a real-life distance between poles of 23 meters (Figure 4). The light height was 30 centimetres, corresponding to 6-meter-high luminaires outdoors. A different perspective view can be seen in Appendix C. The luminaires on the road were not tilted, to avoid a possible increase in glare. Each pole was equipped with LEDs and had lenses mounted that were of the same type as used in the full size road lighting luminaires.

Figure 4. Experimental setup overview with model- and real-life measurements

Philips QuickPlay Pro software controlled a SmartJack Pro connected to EldoLED Powerdrive 106/M DMX drivers. For controlling the light of the poles on the road, custom DMX control software was used for precise lighting adjustments. The illuminance was measured and set up with a LMT B 360 lux meter, according to the scenarios mentioned in section 2.3.1. The spectrum was measured and compared with a Jeti Spectros 1211 spectroradiometer. The contrast, positioning and light measurements were taken at participant perspective with a TechnoTeam LMK Color videophotometer. All measuring equipment was calibrated and corrected for the human vision sensitivity curve $V(\lambda)$. 


During the experiment, response times between the start of the test and the actual pedal input was registered electronically. Speed was relevant in this situation because a large part of the adaptation occurs within the first second (Rinner & Gegenfurtner, 2000). With LabVIEW, a tool was made to automate calling lighting scenes, read pedal input and control the shutters of the adaptation glasses. The adaptation glasses worn by the participant were laboratory safety glasses equipped with mechanical shutters, which opened electronically to perform the visibility tasks (example in Appendix D). On each side of the frame, the same LEDs as on the model road were mounted. The LEDs would reflect light indirectly on the eyes via reflective white plastic in the shutters. The two luminance light settings were similar for each colour and luminance level, on both the model road and in the adaptation glasses. The luminance values for the glasses were obtained by means of a small study (n = 5) in which brightness matching was used to find light settings to which people felt they did not have to adapt. In other words, to find luminance values that were perceptually the same for white light, both in the glasses and on the model road. The coloured light in the glasses was then given the same light level.

2.5. Procedure

Participants were received by the experimenter at the location of the setup. They were given a short introduction, were asked to sign a consent form, and had opportunity to ask questions. Participants were then tested for colour blindness with an Ishihara test and a minimum acuity of their vision was confirmed with a Schnellen chart. After correctly positioning them behind the model road, they were given the instruction to put their right foot on the throttle to recreate the situation of a regular driver. This foot also had to be used for braking. They were not naïve about the experimental purpose and were told that their response time was measured and that the experiment was about speed and accuracy of detecting objects. Also, participants were told that with 2 out of the 24 light transitions in the experiment, no object would appear on the road and they would not have to brake. This was implemented to increase caution, and to counter behaviour of braking first, and finding out where the object was positioned afterwards. They were by default given two trial runs (three if needed) with short adaptation periods, to get familiar with the task and the equipment.

During the main part of the experiment, participants were being adapted for 90 seconds to a colour in the glasses. During adaption the shutters were down, preventing a view on the model road in front of them. After around 80 seconds a verbal warning was given. The adaptation light in the glasses would turn off ten seconds later, and the shutters were simultaneously opened by the computer. Participants had to brake with their electronic pedals when they had seen the object on the road in front of them, illuminated with a different colour. The targets were only presented foveally for a maximum duration of five seconds, as a longer response time could be considered as unacceptable in any real-life situation. The time between the opening of the shutters and the release of the throttle pedal was automatically registered. Immediately after their braking response, participants had to verbally rate the visibility of the object standing on the road. When no braking response had been detected, the participant would proceed with the next transition. As a general precaution to avoid learning and expectations during the experiment, the order in which participants were exposed to the different positions of the objects and colour transitions were different for both light levels. Secondly, the order of which of the two luminance series was shown first, was changed in the conditions as well.

The colour they were presented with during the object visibility test on the road was subsequently used as the colour in the adaptation situation for the next round. For example, when after a white light
adaptation, they were exposed to blue lighting on the road, blue was also used as adaptation for the next transition. This would save adaptation time and limit the amount of times switching between different colours.

2.6. Measures

The response time was measured with electronic pedals, which registered the release of the throttle and the push of the brake for every hundredth of a second. This electronic signal was converted into a digital signal with a National Instruments USB-6353 data acquisition box to create a response graph that was visible on the experimenter’s screen. A shorter response time indicated a better object visibility. If no pedal response was detected it was verified with the participant and registered as a miss. The data of each light transition’s exact response was automatically saved in a folder. This data was imported in Excel, where the response times for all transitions were plotted. The point at which the value of throttle input dropped was determined as the first sign of a braking response, but only if a full brake was registered as well. The plots were carefully checked for faulty input (e.g. reflexes, doubts in reactions, shutters failing to open) or noisy data points, and removed where necessary.

The subjective ratings for object visibility that participants verbally had to give after their pedal input, had a numerical rating scale between 1 (invisible) and 10 (perfectly visible). In other words, a lower rating indicated a worse visibility. The number was entered by the experimenter in the software that controlled the light, to link the response to the right transition. This numerical scale was chosen because it was thought to be something people could easily relate to. Due to darkness during the experiment and because people wore glasses with shutters, it was not possible to present them with scales on paper (e.g. discrete Likert or continuous Visual Analogue Scales).

Both the objective and subjective data was then further analysed with IBM SPSS 22.

22
3. Results

3.1. Dataset

The visual performance was tested by measuring the response times for detecting objects with an equal visibility level, under different types of coloured lighting. Participants response time and visibility rating data was analysed for 11 light transitions on 2 different light levels (2 no-object transitions were deleted, see section 2.5). When the colour green is mentioned, this is referring to a mix of green and red light, as described in section 2.3.2. The maximum time in which participants had to respond was 5000 ms. If no response was measured, transitions were registered as a ‘miss’ (n = 22). No false positives were found.

Exploring the response time data gathered during this experiment, multiple scores did not adhere to the rules for normality. The Kolmogorov-Smirnov and Shapiro-Wilk test indicated several deviations from normality, which was confirmed by the histograms, skewness values and Q-Q plots. Since transformations of the data did not improve normality, the data was treated as non-parametric. Most inferential statistical tests were therefore done with Wilcoxon’s non-parametric analysis, as replacement for the parametric t-test. The test sorts the differences between the transitions that are up for comparison, by their size. They are then ranked, and the sum of these ranks gives positive or negative differences. The null hypothesis is based on a median difference of zero. They are checked for significance by converting the test statistic to a z-score. If larger than 1.96, the test is statistically significant.

3.2. General observations

The general overview of the objective measures (Figure 5) shows the median response times of participants for each of the 11 transitions at both high and low light level conditions. The graph shows that on the low light level condition, the worst transition (white-to-blue, 1880 ms) has a response time which is over two times slower compared to the fastest transition (white-to-white, 845 ms). Another point can be made on the direction of the transitions. All transitions with longer response times are almost always ending with coloured- instead of white light. Furthermore, the two transitions with the longest median response times both end with the blue light colour. In Appendix E, a more detailed overview with the response time distribution for each light transition can be found. That graph shows how the distribution changes from emphasis on the response times longer than three seconds for coloured light, to the shorter response times for white-to-white light transitions.

The subjective visibility measurements, the ratings (Figure 6) give an idea of how participants perceived and judged the object’s visibility during the different light transitions. First of all, the median rating for each of the light transitions fell between a minimum score of 1 and a maximum score of 5. This indicates that objects were in general rated between just visible (5) and invisible (1). Two conditions standing out from the rest are transitions ending with blue light (i.e. red-to-blue and white-to-blue). These two light transitions scored low in subjective visibility for both light levels and stood out in the objective measures graph as well. The last observation is that the light transitions in the high light level condition seem to vary more in their median ratings compared to the low light level condition. However, this trend is not supported in the figure for the response time data.
Figure 5. Median response times (milliseconds) per transition and light level condition (high/low)

Figure 6. Median ratings (1-10) per transition and light level condition (high/low)
3.3. All white versus mixed light transitions

The first hypothesis stated that colours in a light transition would increase the objective response time of participants. To test this hypothesis, a med-based comparison was made between pure white-to-white transitions and all other transitions with a white-to-colour or colour-to-white combination. This was tested with a Bonferroni corrected, one-sided, Wilcoxon matched-pairs signed rank test. It was found that for the white-to-white transition in the high light level condition, the median response times were significantly shorter (Mdn = 970 ms) compared to all the other transitions involving colour (Mdn = 1230 ms), with $T = 27$, $p \leq 0.001$, $r = -.45$. For the low light level condition, the hypothesis was supported as well, with the white-to-white transition resulting in significantly shorter response times (Mdn = 845 ms) compared to the group of transitions with colour (Mdn = 980 ms), with $T = 38$, $p \leq 0.001$, $r = -.41$. In both light level situations, the white-to-white transition appears to have significantly shorter response times, with a difference between the medians of 260 ms in the high light level condition and a 135 ms difference in the low light level condition compared to the mixed light transitions. The effect sizes were large (Cohen, 1988).

The subjective visibility ratings showed a trend for the high light level conditions, with lower visibility ratings for white-to-white light transitions (Mdn = 2.0) compared to the mixed light transitions (Mdn = 2.5), with $T = 99.5$, $p < 0.077$, $r = -.20$, although this difference was not statistically significant. However, on low light level conditions the white-to-white transition rating (Mdn = 4) was significantly higher than mixed colour transitions ratings (Mdn = 4), with $T = 20$, $p \leq 0.001$, $r = -.49$.

When comparing white-to-white transitions on each light level with all other individual transitions in a pair-wise fashion, the light transitions with colour caused in absolute numbers a longer response time. Some of these comparisons gave significant results on the one-sided Wilcoxon signed rank test, after a strict Bonferroni correction (where $p = .05$ divided by 10 transitions $= p = 0.005$). These transitions are marked with an asterisk in Table 2. The possibility of finding these effects by chance was therefore low, and the effect sizes of the significant values are medium to large (Cohen, 1988). In other words, white-to-white light transitions do, in general, result in better performance (i.e. shorter response times) compared to transitions in which coloured light is used, no matter the light level. Looking at the specific transitions, significant results appear to be observed mostly on transitions from white light to coloured lighting. The difference in response times between these mixed- and white-to-white light transitions, support the expected impairing effects on the visual performance as stated in the first hypothesis.

### Table 2. Comparison between white-to-white and mixed light transition response times

<table>
<thead>
<tr>
<th>Medians, Wilcoxon statistic, significances and effect sizes for reported comparisons.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transition</strong></td>
</tr>
<tr>
<td>White-Red</td>
</tr>
<tr>
<td>White-Green</td>
</tr>
<tr>
<td>White-Blue</td>
</tr>
<tr>
<td>White-Amber</td>
</tr>
<tr>
<td>Red-White</td>
</tr>
<tr>
<td>Green-White</td>
</tr>
<tr>
<td>Blue-White</td>
</tr>
<tr>
<td>Amber-White</td>
</tr>
<tr>
<td>Red-Blue</td>
</tr>
<tr>
<td>Blue-Red</td>
</tr>
</tbody>
</table>
Low light level condition. A white-to-white transition (Mdn = 845 ms) compared to:

<table>
<thead>
<tr>
<th>Transition</th>
<th>Median</th>
<th>T</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>980</td>
<td>36.0</td>
<td>.002*</td>
<td>-0.42</td>
</tr>
<tr>
<td>White-Green</td>
<td>1015</td>
<td>68.5</td>
<td>.053</td>
<td>-0.25</td>
</tr>
<tr>
<td>White-Blue</td>
<td>1880</td>
<td>9.0</td>
<td>.000*</td>
<td>-0.56</td>
</tr>
<tr>
<td>White-Amber</td>
<td>1010</td>
<td>29.0</td>
<td>.001*</td>
<td>-0.46</td>
</tr>
<tr>
<td>Red-White</td>
<td>950</td>
<td>53.0</td>
<td>.082</td>
<td>-0.23</td>
</tr>
<tr>
<td>Green-White</td>
<td>905</td>
<td>86.5</td>
<td>.100</td>
<td>-0.20</td>
</tr>
<tr>
<td>Blue-White</td>
<td>970</td>
<td>61.5</td>
<td>.093</td>
<td>-0.21</td>
</tr>
<tr>
<td>Amber-White</td>
<td>950</td>
<td>65.0</td>
<td>.040</td>
<td>-0.27</td>
</tr>
<tr>
<td>Red-Blue</td>
<td>1340</td>
<td>13.0</td>
<td>.003*</td>
<td>-0.49</td>
</tr>
<tr>
<td>Blue-Red</td>
<td>950</td>
<td>71.5</td>
<td>.038</td>
<td>-0.27</td>
</tr>
</tbody>
</table>

*Note: Significant differences after the stricter p ≤ .005 Bonferroni correction are marked with an *

3.4. Direction of mixed light transitions

The second expectation was that transitions ending with coloured light would increase the objective response time of participants. To test this hypothesis, colour-to-white transitions were compared to white-to-colour transitions. To test whether response times were longer in one of the transition directions on each light level, there were four transitions used in each of the two groups. For example, the white-to-colour group contains the white-to-red, white-to-green, white-to-blue and white-to-amber transitions. The transitions in opposite direction are in the other group (e.g. red-to-white). The results of the directional Wilcoxon signed rank test indicated that for the high light level conditions, transitions ending with coloured light had significantly longer response times (Mdn = 1390 ms) compared to the transitions ending with white light (Mdn = 1210 ms), with T = 63, p ≤ 0.01, r = -0.38. For the low light level condition this effect was also observed, where the white-to-colour transitions had significantly longer response times (Mdn = 1223 ms) compared to the group of transitions ending with white light (Mdn = 955 ms), with T = 24, p ≤ 0.001, r = -0.52. These directional effect differences with respectively 180 ms and 268 ms are smaller compared to the previous white versus colour effect, but support the hypothesis with medium to large effect sizes.

When looking at the subjective ratings, the hypothesis was partially confirmed with higher visibility ratings for colour-to-white light transitions (Mdn = 4.25) compared to the white-to-colour transitions (Mdn = 3.5), but only at the low light level condition, with T = 27, p ≤ 0.001, r = -0.48. For the high light level condition this effect was also significant, but in the opposite direction. The colour-to-white light transition rating (Mdn = 2.25) was hereby lower compared to the white-to-colour light transitions (Mdn = 3), with T = 71.5, p ≤ 0.05, r = -0.29.

When comparing the coloured light transitions in both directions for each colour separately, there is a trend visible. For all colours the difference is in the same direction, and half of these transitions appear to have significant longer response times when ending with a colour (Table 3). However, after a stricter Bonferroni corrected significance (p = .05 divided by 4 comparisons gives p = 0.0125), only the blue-to-white and white-to-blue transitions are for both light levels significantly different with large effect sizes. These differences in response times are also relatively large, with differences of over 900 ms; due only to the direction of the transition. Without the strict Bonferroni correction, the high light level white-red transition and the low light level white-amber transition are significantly different as well.
Table 3. Comparison of response times between mixed light transitions in different directions
*Medians, Wilcoxon statistic, significances and effect sizes for reported comparisons.*

<table>
<thead>
<tr>
<th>High light level condition:</th>
<th>Transition</th>
<th>Median</th>
<th>Transition</th>
<th>Median</th>
<th>T</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>1460</td>
<td>Red-White</td>
<td>1330</td>
<td>39</td>
<td>.022</td>
<td>-.34</td>
<td></td>
</tr>
<tr>
<td>White-Green</td>
<td>1180</td>
<td>Green-White</td>
<td>1100</td>
<td>100.5</td>
<td>.205</td>
<td>-.13</td>
<td></td>
</tr>
<tr>
<td>White-Blue</td>
<td>1850</td>
<td>Blue-White</td>
<td>1150</td>
<td>14</td>
<td>.000*</td>
<td>-.52</td>
<td></td>
</tr>
<tr>
<td>White-Amber</td>
<td>1230</td>
<td>Amber-White</td>
<td>1050</td>
<td>55.5</td>
<td>.100</td>
<td>-.21</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low light level condition:</th>
<th>Transition</th>
<th>Median</th>
<th>Transition</th>
<th>Median</th>
<th>T</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>980</td>
<td>Red-White</td>
<td>950</td>
<td>64.5</td>
<td>.115</td>
<td>-.20</td>
<td></td>
</tr>
<tr>
<td>White-Green</td>
<td>1015</td>
<td>Green-White</td>
<td>905</td>
<td>86</td>
<td>.158</td>
<td>-.15</td>
<td></td>
</tr>
<tr>
<td>White-Blue</td>
<td>1880</td>
<td>Blue-White</td>
<td>970</td>
<td>11.5</td>
<td>.001*</td>
<td>-.50</td>
<td></td>
</tr>
<tr>
<td>White-Amber</td>
<td>1010</td>
<td>Amber-White</td>
<td>950</td>
<td>24</td>
<td>.038</td>
<td>-.28</td>
<td></td>
</tr>
</tbody>
</table>

*Note: Significant differences after the stricter p ≤ .0125 Bonferroni correction are marked with an *

Overall, these results partially confirm the hypothesis that light transitions towards a colour have a longer response time compared to colour-to-white lighting transitions. Overall, transitions towards coloured lighting resulted in larger response times, and a group comparison showed this significance as well. Subjective measures at group level gave significant differences for the low light level transitions too. When analysing individual transitions separately, this was mostly a trend and only the transitions with blue light appeared statistically significant at both the high and low light level.

3.5. Blue based light transitions

The third hypothesis stated that longer response times would be observed in light transitions which included blue light. To test this prediction, the white-to-blue and blue-to-white light transitions were compared with all other transitions. Consistent with this hypothesis were the relatively large number of misses for transitions that included blue light (*Table 4*). Except for the amber-to-white transition, no other colour transition had any misses due to invisible objects. This appears to support the hypothesis that blue had quite an adverse effect on object visibility. Furthermore, the effect was present in more different transitions in the higher light level conditions, although the absolute number of total misses was equal.

A group comparison with a Wilcoxon signed rank test showed that for transitions with the blue colour in the high light level condition, the response times were significantly longer (*Mdn = 1410 ms*) compared to the transitions without blue light (*Mdn = 1170 ms*), with *T = 44.5, p ≤ .01, r = -.42*. For the low light level condition this effect was also observed, with longer response times for transitions involving blue light (*Mdn = 1110 ms*) compared to the group of transitions without blue light (*Mdn = 965 ms*), with *T = 42.5, p ≤ 0.001, r = -.46*. As mentioned, this outcome was highly significant, even

Table 4. Number of misses per light transition
*Overview of light transitions with not detected objects. Absolute and relative misses of total exposures.*

<table>
<thead>
<tr>
<th>High light level condition:</th>
<th>Transition</th>
<th>Misses</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Blue</td>
<td>4</td>
<td>16%</td>
<td></td>
</tr>
<tr>
<td>Blue-White</td>
<td>1</td>
<td>4%</td>
<td></td>
</tr>
<tr>
<td>Amber-White</td>
<td>3</td>
<td>12%</td>
<td></td>
</tr>
<tr>
<td>Red-Blue</td>
<td>3</td>
<td>12%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low light level condition:</th>
<th>Transition</th>
<th>Misses</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Blue</td>
<td>4</td>
<td>16%</td>
<td></td>
</tr>
<tr>
<td>Red-Blue</td>
<td>7</td>
<td>28%</td>
<td></td>
</tr>
</tbody>
</table>
though multiple blue light transitions were not included in the analysis because they were registered as misses. The difference between the two light level groups was 145 ms (low light level condition) and 240 ms (high light level condition). This comparison did include the experimental red-to-blue or blue-to-red transitions that are not encountered in real-life lighting scenarios. A comparison which did not include these experimental transitions, gave even larger significant differences.

Considering the subjective visibility ratings, transitions with blue were rated lower (Mdn = 2), compared to non-blue light transitions in the high light level condition (Mdn = 2.6), with \( T = 27, p \leq 0.001, r = -0.47 \). For the low light level condition this was true as well, with blue light containing transitions having significant lower ratings (Mdn = 3), compared to non-blue light transitions (Mdn = 4.14), with \( T = 17.5, p \leq 0.001, r = -.54 \). These subjective ratings thereby confirm the effect observed with the objectively measured response times.

When comparing blue-based transitions to all other transitions individually by means of a Wilcoxon signed rank test, a clear trend was observed. For both light levels, the mixed transitions towards blue light were all significant (Bonferroni corrected; \( p = .05 \) divided by 4 transitions is \( p = .0125 \)) with large effect sizes (Table 5). The light transitions blue-to-white light mostly had a longer (median) response time as well, but these effects were not statistically significant.

These results thereby (partially) support the third hypothesis in that blue light will cause more visibility problems compared to transitions involving other colours. However, the effect is only significant for transitions to blue light. It thereby also supports the previous hypothesis that transitions towards a colour had a much larger negative effect on visibility compared to transitions towards white light. The differences in range between transitions ending on colours are also much larger (up to 900 ms) compared to what can be observed in transitions towards white (up to 180 ms).

Table 5. Comparison of response times between transitions with- and without blue light

<table>
<thead>
<tr>
<th>High light level condition. A white-to-blue transition (Mdn = 1850 ms) compared to:</th>
<th>Median</th>
<th>T</th>
<th>( p )</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>1460</td>
<td>21</td>
<td>.007*</td>
<td>-0.42</td>
</tr>
<tr>
<td>White-Green</td>
<td>1180</td>
<td>20</td>
<td>.001*</td>
<td>-0.49</td>
</tr>
<tr>
<td>White-Amber</td>
<td>1230</td>
<td>13</td>
<td>.000*</td>
<td>-0.53</td>
</tr>
<tr>
<td>White-White</td>
<td>970</td>
<td>12</td>
<td>.000*</td>
<td>-0.54</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High light level condition. A blue-to-white transition (Mdn = 1150 ms) compared to:</th>
<th>Median</th>
<th>T</th>
<th>( p )</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red-White</td>
<td>1330</td>
<td>64</td>
<td>.289</td>
<td>-0.10</td>
</tr>
<tr>
<td>Green-White</td>
<td>1100</td>
<td>134.5</td>
<td>.141</td>
<td>-0.17</td>
</tr>
<tr>
<td>Amber-White</td>
<td>1050</td>
<td>100</td>
<td>.272</td>
<td>-0.11</td>
</tr>
<tr>
<td>White-White</td>
<td>970</td>
<td>154</td>
<td>.034</td>
<td>-0.29</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Low light level condition. A white-to-blue transition (Mdn = 1880 ms) compared to:</th>
<th>Median</th>
<th>T</th>
<th>( p )</th>
<th>( r )</th>
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</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>980</td>
<td>158.5</td>
<td>.000*</td>
<td>-0.53</td>
</tr>
<tr>
<td>White-Green</td>
<td>1015</td>
<td>178</td>
<td>.000*</td>
<td>-0.54</td>
</tr>
<tr>
<td>White-Amber</td>
<td>1010</td>
<td>167</td>
<td>.001*</td>
<td>-0.47</td>
</tr>
<tr>
<td>White-White</td>
<td>845</td>
<td>162</td>
<td>.000*</td>
<td>-0.56</td>
</tr>
</tbody>
</table>
Low light level condition. A blue-to-white transition \((Mdn = 970 \text{ ms})\) compared to:

<table>
<thead>
<tr>
<th>Transition</th>
<th>Median</th>
<th>T</th>
<th>(p)</th>
<th>(r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red-White</td>
<td>950</td>
<td>115.5</td>
<td>.354</td>
<td>-.06</td>
</tr>
<tr>
<td>Green-White</td>
<td>905</td>
<td>123.5</td>
<td>.252</td>
<td>-.11</td>
</tr>
<tr>
<td>Amber-White</td>
<td>950</td>
<td>136.5</td>
<td>.378</td>
<td>-.05</td>
</tr>
<tr>
<td>White-White</td>
<td>845</td>
<td>128.5</td>
<td>.093</td>
<td>-.21</td>
</tr>
</tbody>
</table>

Note: Significant differences after the stricter \(p \leq .0125\) Bonferroni correction are marked with an *.

### 3.6. Experimental full-colour light transitions

The fourth hypothesis states that light transitions involving extreme colours in the visual spectrum (Eloholma et al., 2006) and on different cardinal axes in the opponent colour theory (section 1.2.1) would result in a larger detrimental effect on visual performance (i.e. longer response times) compared to other mixed transitions. This hypothesis was tested with a purely experimental light transition, not based on existing real-life outdoor lighting scenarios. It was expected that the switching between two strong and opposite colours, would cause even larger response times among participants compared to other mixed light transitions. A group comparison between these red-to-blue and blue-to-red transitions and all other transitions was made. The directional Wilcoxon signed rank test, revealed that for the high light level conditions the red-to-blue and blue-to-red transitions \((Mdn = 1520 \text{ ms})\) had indeed longer response times compared to all other transitions \((Mdn = 1301 \text{ ms})\), with \(T = 88, p \leq .023, r = -.28\). However, for the low light level conditions the special transitions \((Mdn = 1095 \text{ ms})\) did not result in longer response times than the other transitions \((Mdn = 1109 \text{ ms})\), and the difference was not statistically significant with \(T = 143.5, p < .310\), and \(r = -.07\).

The subjective visibility ratings showed trends in a similar direction. On a group level, the scores on the high light level condition were found to be significantly different for the red-to-blue and blue-to-red combinations \((Mdn = 2)\) compared to the other light transitions \((Mdn = 2.44)\), with \(T = 85.5, p < .05\), and \(r = -.26\). Similar effects were found in the low light level condition between the red-to-blue and blue-to-red light combinations \((Mdn = 3)\) compared to all other transitions \((Mdn = 4)\), with \(T = 79.5, p < .05\), and \(r = -.25\).

When the transitions are individually examined with the Wilcoxon analysis (Table 6), multiple comparisons have significantly longer response times for the red-blue light transition combinations, even when using a stricter Bonferroni correction \((p = .05\) divided by 9 transitions gives \(p = .006)\). Other comparisons show a strong similar trend in the same direction but are not significant after the Bonferroni correction. However, these transitions are worth taking into account as well, considering their medium to large effect sizes.

It is worth mentioning that there are two values (in bold in Table 6) on both the high and low light level comparisons that are significant, but in the opposite direction. In other words, in these two cases red-to-blue or blue-to-red transitions are better than the transitions it was compared with. In three out of four cases this was another transition ending with blue light (i.e. white-blue), which is worse compared to the red-blue combination, as was also seen in section 3.5. Furthermore, the trend in which the light transitions towards blue yielded more (almost) significant differences, can also be observed in this table (especially on the low light level condition). This further supports the earlier conclusions about adverse effects for blue light, mentioned in section 3.5.

It should be noted that the white-to-blue transitions miss on each light level condition four cases due to
missed objects by participants (thus 8 out of 50 for that transition alone). The same situation applies to
the red-to-blue light transitions, which misses no less than 10 out of 50 data points. It is therefore very
likely that without these misses, all the blue transitions would have been significant because the medians
differ a lot. After all, these misses likely also consist of longer response times beyond the maximum
allowed timespan of five seconds. Looking at the limited remaining data, it is expected that white-to-
blue transitions are indeed worse compared to red-to-blue transitions. The latter is having response
times more comparable to other light transitions. The fourth hypothesis is therefore considered as only
partially confirmed. The special coloured transitions do have a very long response time compared to
the rest of the transitions, but is second instead of first as the worst light transition.

Table 6. Comparison of response times between with- and without blue-red (or red-blue) transitions
Medians, Wilcoxon statistic, significances and effect sizes for reported comparisons.

<table>
<thead>
<tr>
<th>High light level condition. A red-to-blue transition ($Mdn = 1420$ ms) compared to:</th>
<th>Median</th>
<th>$T$</th>
<th>$p$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>1460</td>
<td>77.5</td>
<td>.371</td>
<td>-0.06</td>
</tr>
<tr>
<td>White-Green</td>
<td>1180</td>
<td>57.5</td>
<td>.068</td>
<td>-0.24</td>
</tr>
<tr>
<td>White-Blue</td>
<td>1850</td>
<td>40.0</td>
<td>.044</td>
<td>-0.29</td>
</tr>
<tr>
<td>White-Amber</td>
<td>1230</td>
<td>41.5</td>
<td>.028</td>
<td>-0.32</td>
</tr>
<tr>
<td>White-White</td>
<td>970</td>
<td>36.0</td>
<td>.004*</td>
<td>-0.41</td>
</tr>
<tr>
<td>Red-White</td>
<td>1330</td>
<td>66.0</td>
<td>.209</td>
<td>-0.14</td>
</tr>
<tr>
<td>Green-White</td>
<td>1100</td>
<td>38.0</td>
<td>.010</td>
<td>-0.37</td>
</tr>
<tr>
<td>Blue-White</td>
<td>1150</td>
<td>49.5</td>
<td>.061</td>
<td>-0.26</td>
</tr>
<tr>
<td>Amber-White</td>
<td>1050</td>
<td>23.5</td>
<td>.002*</td>
<td>-0.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High light level condition. A blue-to-red transition ($Mdn = 1300$ ms) compared to:</th>
<th>Median</th>
<th>$T$</th>
<th>$p$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>1460</td>
<td>85.0</td>
<td>.237</td>
<td>-0.12</td>
</tr>
<tr>
<td>White-Green</td>
<td>1180</td>
<td>81.0</td>
<td>.042</td>
<td>-0.26</td>
</tr>
<tr>
<td>White-Blue</td>
<td>1850</td>
<td>28.0</td>
<td>.001*</td>
<td>-0.45</td>
</tr>
<tr>
<td>White-Amber</td>
<td>1230</td>
<td>78.5</td>
<td>.061</td>
<td>-0.23</td>
</tr>
<tr>
<td>White-White</td>
<td>970</td>
<td>34.0</td>
<td>.001*</td>
<td>-0.44</td>
</tr>
<tr>
<td>Red-White</td>
<td>1330</td>
<td>94.5</td>
<td>.239</td>
<td>-0.11</td>
</tr>
<tr>
<td>Green-White</td>
<td>1100</td>
<td>47.0</td>
<td>.002*</td>
<td>-0.41</td>
</tr>
<tr>
<td>Blue-White</td>
<td>1150</td>
<td>65.0</td>
<td>.041</td>
<td>-0.27</td>
</tr>
<tr>
<td>Amber-White</td>
<td>1050</td>
<td>23.5</td>
<td>.000*</td>
<td>-0.49</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low light level condition. A red-to-blue transition ($Mdn = 1340$ ms) compared to:</th>
<th>Median</th>
<th>$T$</th>
<th>$p$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>980</td>
<td>16.0</td>
<td>.003*</td>
<td>-0.48</td>
</tr>
<tr>
<td>White-Green</td>
<td>1015</td>
<td>15.5</td>
<td>.002*</td>
<td>-0.48</td>
</tr>
<tr>
<td>White-Blue</td>
<td>1880</td>
<td>28.5</td>
<td>.070</td>
<td>-0.28</td>
</tr>
<tr>
<td>White-Amber</td>
<td>1010</td>
<td>36.5</td>
<td>.054</td>
<td>-0.29</td>
</tr>
<tr>
<td>White-White</td>
<td>845</td>
<td>13.0</td>
<td>.003*</td>
<td>-0.49</td>
</tr>
<tr>
<td>Red-White</td>
<td>950</td>
<td>19.0</td>
<td>.009</td>
<td>-0.43</td>
</tr>
<tr>
<td>Green-White</td>
<td>905</td>
<td>10.0</td>
<td>.001*</td>
<td>-0.52</td>
</tr>
<tr>
<td>Blue-White</td>
<td>970</td>
<td>27.0</td>
<td>.017</td>
<td>-0.37</td>
</tr>
<tr>
<td>Amber-White</td>
<td>950</td>
<td>28.5</td>
<td>.020</td>
<td>-0.36</td>
</tr>
</tbody>
</table>
Low light level condition. A blue-to-red transition ($Mdn = 950$ ms) compared to:

<table>
<thead>
<tr>
<th>Transition</th>
<th>Median</th>
<th>$T$</th>
<th>$p$</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>980</td>
<td>97.5</td>
<td>.113</td>
<td>-0.18</td>
</tr>
<tr>
<td>White-Green</td>
<td>1015</td>
<td>109.0</td>
<td>.125</td>
<td>-0.17</td>
</tr>
<tr>
<td>White-Blue</td>
<td><strong>1880</strong></td>
<td>13.0</td>
<td>.000*</td>
<td>-0.54</td>
</tr>
<tr>
<td>White-Amber</td>
<td><strong>1010</strong></td>
<td>55.5</td>
<td>.005*</td>
<td>-0.37</td>
</tr>
<tr>
<td>White-White</td>
<td>845</td>
<td>71.5</td>
<td>.038</td>
<td>-0.27</td>
</tr>
<tr>
<td>Red-White</td>
<td>950</td>
<td>98.0</td>
<td>.403</td>
<td>-0.04</td>
</tr>
<tr>
<td>Green-White</td>
<td>905</td>
<td>125.5</td>
<td>.490</td>
<td>0.00</td>
</tr>
<tr>
<td>Blue-White</td>
<td>970</td>
<td>93.0</td>
<td>.143</td>
<td>-0.16</td>
</tr>
<tr>
<td>Amber-White</td>
<td>950</td>
<td>103.5</td>
<td>.234</td>
<td>-0.11</td>
</tr>
</tbody>
</table>

Note: Significant differences after the stricter $p \leq .006$ Bonferroni correction are marked with an *

### 3.7. High versus low light level transitions

The fifth hypothesis stated that high light level conditions would increase the visual performance, and thereby reduce the detrimental effects with coloured light at lower luminances. The response time of participants was therefore expected to decrease in high as compared to low light level conditions. To test this hypothesis, a group comparison was made between the response time of all high light level transitions combined with that of all low light transitions combined. A Wilcoxon matched-pairs signed rank test between the two light levels indicated that the high light level condition ($Mdn = 1250$ ms) caused significantly more disturbance to object detection (i.e. a longer response time) compared to the low light level condition ($Mdn = 980$ ms), with $T = 0, p \leq .001$, and $r = -.62$. The differences in response times due to light level alone, hereby reached a 270 ms difference and the effect size was large. For the subjective visibility ratings, a similar trend between high light level transitions ($Mdn = 2.36$) and low light level transitions ($Mdn = 3.91$) was found, with $T = 3, p \leq .001$, $r = -.59$. In other words, the lower visibility ratings for higher light level condition seemed to confirm the analysis of the objective response times.

In addition to the main comparison, a post-hoc test compared the individual pairs of transitions at different light levels by means of a Wilcoxon signed rank test. The results show that almost each transition had a longer response time in the high light level condition (Table 7). Five of these comparisons were significant after a stricter Bonferroni correction ($p = .05$ divided by 11 transitions gives $p = .005$), with at least medium effect sizes. Two other comparisons were close to this significance level as well. Although some differences in medians were almost equal for the same transitions between the light levels (e.g. white-to-blue), others were rather large with up to 480 ms differences (e.g. white-to-red). This analysis thereby confirms the above mentioned results that higher light levels led to worse visual performance. It is therefore concluded that in contrast to what was expected, a higher light level seems to result in longer response times.
Table 7. Comparison of response times of similar transitions between different light levels  
Medians, Wilcoxon statistic, significances and effect sizes for reported comparisons.

<table>
<thead>
<tr>
<th>Low light level</th>
<th>Transition</th>
<th>Median</th>
<th>High light level</th>
<th>Transition</th>
<th>Median</th>
<th>T</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>980</td>
<td></td>
<td>White-Red</td>
<td>1460</td>
<td>0.0</td>
<td>.000*</td>
<td>-0.62</td>
<td></td>
</tr>
<tr>
<td>White-Green</td>
<td>1015</td>
<td></td>
<td>White-Green</td>
<td>1180</td>
<td>53.5</td>
<td>.008</td>
<td>-0.36</td>
<td></td>
</tr>
<tr>
<td>White-Blue</td>
<td>1880</td>
<td></td>
<td>White-Blue</td>
<td>1850</td>
<td>76.0</td>
<td>.500</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>White-Amber</td>
<td>1010</td>
<td></td>
<td>White-Amber</td>
<td>1230</td>
<td>98.5</td>
<td>.284</td>
<td>-0.09</td>
<td></td>
</tr>
<tr>
<td>White-White</td>
<td>845</td>
<td></td>
<td>White-White</td>
<td>970</td>
<td>40.0</td>
<td>.002*</td>
<td>-0.42</td>
<td></td>
</tr>
<tr>
<td>Red-White</td>
<td>950</td>
<td></td>
<td>Red-White</td>
<td>1330</td>
<td>10.0</td>
<td>.000*</td>
<td>-0.55</td>
<td></td>
</tr>
<tr>
<td>Green-White</td>
<td>905</td>
<td></td>
<td>Green-White</td>
<td>1100</td>
<td>7.0</td>
<td>.000*</td>
<td>-0.58</td>
<td></td>
</tr>
<tr>
<td>Blue-White</td>
<td>970</td>
<td></td>
<td>Blue-White</td>
<td>1150</td>
<td>35.0</td>
<td>.013</td>
<td>-0.36</td>
<td></td>
</tr>
<tr>
<td>Amber-White</td>
<td>950</td>
<td></td>
<td>Amber-White</td>
<td>1050</td>
<td>64.0</td>
<td>.065</td>
<td>-0.24</td>
<td></td>
</tr>
<tr>
<td>Red-Blue</td>
<td>1340</td>
<td></td>
<td>Red-Blue</td>
<td>1420</td>
<td>63.0</td>
<td>.406</td>
<td>-0.05</td>
<td></td>
</tr>
<tr>
<td>Blue-Red</td>
<td>950</td>
<td></td>
<td>Blue-Red</td>
<td>1300</td>
<td>1.5</td>
<td>.000*</td>
<td>-0.61</td>
<td></td>
</tr>
</tbody>
</table>

Note: Significant differences after the stricter p ≤ .005 Bonferroni correction are marked with an *

3.8. Correlation of subjective and objective measures

To investigate the extent to which participants’ subjective visibility ratings could accurately predict performance, both subjective visibility ratings and objective response times were measured during the experiment. The sixth hypothesis stated that people’s ratings for visibility would not accurately predict actual visual performance. A correlation analysis was executed between all the average object ratings per transition with all objectively measured response times. Of the 11 transitions in both light level conditions, only for the white-to-amber transition shown in Table 8 there was a significant correlation between subjective and objective measurements (after Bonferroni correction; p = .05 divided by 11 transitions gives p = .005).

The fact that only one of the light transition’s correlation was statistically significant, makes it look like a relation with minor consequences. There is no trend, theory or reason that points in the direction to believe that this correlation was important for this study with coloured light. However, these correlations do seem to confirm the link between subjective and objective measurements for amber and white lighting (mentioned in section 1.4) as found by Janoff and Havard (1997). Nonetheless, based on these results there is too little proof to suggest that the few significant correlations are part of a larger effect for coloured light transitions. It therefore seems unlikely that people’s subjective ratings of visibility are an accurate predictive measure for visual performance during transitions with coloured light. Therefore, even though it was found that the subjective ratings often confirmed analyses and conclusions for

Table 8. Correlations between rating and response time for similar transitions  
Transition comparison, correlations and their significance.

<table>
<thead>
<tr>
<th>High light level condition, correlation for:</th>
<th>Transition</th>
<th>Corr.</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-White</td>
<td>-.428</td>
<td>.041</td>
<td></td>
</tr>
<tr>
<td>Blue-Red</td>
<td>-.500</td>
<td>.011</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low light level condition, correlation for:</th>
<th>Transition</th>
<th>Corr.</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>White-Red</td>
<td>-.431</td>
<td>.040</td>
<td></td>
</tr>
<tr>
<td>White-Amber</td>
<td>-.588</td>
<td>.003*</td>
<td></td>
</tr>
<tr>
<td>White-White</td>
<td>-.362</td>
<td>.097</td>
<td></td>
</tr>
</tbody>
</table>

Note: Significant differences after the stricter p ≤ .005 Bonferroni correction are marked with an *
hypotheses that were drawn on the basis of objective performance measurements, no correlation between the two was found on transition level.

When testing for correlations on an individual participant’s level, the outcome is different (Table 9). If all subjective ratings and objective measurements at both light levels are tested, there are multiple statistically significant outcomes, even after Bonferroni correction ($p = 0.05$ divided by 25 participants gives $p = 0.002$). When the graphs of the three participants with the highest and lowest correlations are plotted (Appendix F), a general trend can be identified. An example of a high correlation is plotted in Figure 7. It appears that the lower the ratings, the longer the response times get. In other words, there is a link between the two measures, although this relation is not accurate and significant enough to speak of a good and predictive subjective measure for visual performance. After all, the rating ‘6’ gave for example quite different response times, varying between approximately 800 ms and 1300 ms (Figure 7). A graph which plots all visibility ratings and response times can be found in Appendix G.

### Table 9. Correlations between rating and response time per participant
Correlations and their significance over all transitions and light levels.

<table>
<thead>
<tr>
<th>Participant #</th>
<th>Corr.</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Participant 16</td>
<td>-0.832</td>
<td>.000*</td>
</tr>
<tr>
<td>Participant 21</td>
<td>-0.803</td>
<td>.000*</td>
</tr>
<tr>
<td>Participant 5</td>
<td>-0.802</td>
<td>.000*</td>
</tr>
<tr>
<td>Participant 14</td>
<td>-0.757</td>
<td>.000*</td>
</tr>
<tr>
<td>Participant 22</td>
<td>-0.701</td>
<td>.001*</td>
</tr>
<tr>
<td>Participant 1</td>
<td>-0.691</td>
<td>.000*</td>
</tr>
<tr>
<td>Participant 26</td>
<td>-0.659</td>
<td>.008</td>
</tr>
<tr>
<td>Participant 20</td>
<td>-0.653</td>
<td>.002*</td>
</tr>
<tr>
<td>Participant 11</td>
<td>-0.650</td>
<td>.002*</td>
</tr>
<tr>
<td>Participant 23</td>
<td>-0.644</td>
<td>.032</td>
</tr>
<tr>
<td>Participant 18</td>
<td>-0.604</td>
<td>.004</td>
</tr>
<tr>
<td>Participant 25</td>
<td>-0.587</td>
<td>.008</td>
</tr>
<tr>
<td>Participant 10</td>
<td>-0.517</td>
<td>.016</td>
</tr>
<tr>
<td>Participant 6</td>
<td>-0.512</td>
<td>.035</td>
</tr>
<tr>
<td>Participant 7</td>
<td>-0.509</td>
<td>.019</td>
</tr>
<tr>
<td>Participant 24</td>
<td>-0.488</td>
<td>.029</td>
</tr>
<tr>
<td>Participant 27</td>
<td>-0.486</td>
<td>.035</td>
</tr>
<tr>
<td>Participant 15</td>
<td>-0.484</td>
<td>.022</td>
</tr>
<tr>
<td>Participant 2</td>
<td>-0.470</td>
<td>.027</td>
</tr>
<tr>
<td>Participant 4</td>
<td>-0.426</td>
<td>.054</td>
</tr>
<tr>
<td>Participant 13</td>
<td>-0.402</td>
<td>.064</td>
</tr>
<tr>
<td>Participant 3</td>
<td>-0.397</td>
<td>.115</td>
</tr>
<tr>
<td>Participant 17</td>
<td>-0.396</td>
<td>.084</td>
</tr>
<tr>
<td>Participant 12</td>
<td>-0.393</td>
<td>.078</td>
</tr>
<tr>
<td>Participant 8</td>
<td>-0.305</td>
<td>.424</td>
</tr>
<tr>
<td>Participant 9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Participant 19</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: Significant differences after the stricter $p \leq 0.002$ Bonferroni correction are marked with an *
Overall, based on the overall correlations in each light transitions between objective and subjective measures, there is no direct link between ratings and response times. Within each individual participant there is a correlation between these two measures, even though it has very limited accuracy. The link is therefore barely useful in practice. Therefore, the sixth hypothesis is considered to be at least partially true.

3.9. Correlation of other measures

Other measures registered during the experiment, such as gender, age, condition and whether participants were wearing lenses or glasses, have each been tested for correlation with participant objective response times and subjective ratings. Of all correlations between the objective measures for all transitions on both light levels, there were only two significant correlations after a Bonferroni correction ($p = .05$ divided by 11 transitions gives $p = .005$). These correlations were significant between age and participant response times for the low light level white-to-white transition, $r = -.668, p \leq .001$ and for the high light level white-to-green light transition $r = .572, p \leq .004$. For the subjective ratings, there were no statistically significant results found for any of the transitions at neither of the light levels. The two correlations that were found were high, but seem rather arbitrary. These transitions lack any expected connection or similarity with results found in analysis for the other coloured light transitions, suggesting that none of these factors were influencing earlier results. These analyses do not influence the results of the other analyses and are therefore not discusses further.
4. Discussion

4.1. General

The introduction of LEDs offered the technical possibilities to change the ways in which roads are lit. For car drivers, road lighting is mainly meant to increase the general visibility and to avoid accidents from happening. This means that in general, making objects on the road clearly visible is an important requirement for any type of road lighting. The trend of coloured road lighting first emerged in some places in the Netherlands, and so far similar observations in other countries have not appeared yet, apart from coloured bat-friendly lighting research in the UK. The coloured road lighting is currently implemented without a sufficient understanding of its implications and impact on visibility, in particular for the detection of objects. Differences in spectral sensitivity as mapped with $V(\lambda)$ (i.e. luminous efficiency function) could for example influence the visibility of the same object, under similar lighting circumstances with different colours. The consequences of this were addressed in this experiment.

In this experiment, coloured road lighting conditions were recreated on an indoor scale model. Judging by the subjective ratings and objective measurements in this experiment, the light transitions were implemented at levels where visual performance differences between light conditions could be observed. The few misses indicated that the lowest visibility was close to the border of visual performance, and the range in subjective ratings confirmed that the task was almost constantly at the border of visibility, and only occasionally invisible. Other measured factors that could have influenced these results, such as age, gender, condition and corrected acuity, turned out to be unrelated and did not affect the results. Although more variables, such as oncoming car headlights, clothing or coloured objects could make the experiment more realistic, previous experiments (Terry and Gibbons, 2011) showed this is harder to control. The current experiment therefore made use of a simplified setup in which outdoor conditions were recreated on a model street indoors. This contributed to a high environmental validity, while simultaneously giving more experimental control. The results gave increasing insight in effects on visual performance of road users, when coloured road lighting is applied.

4.2. Main effects

4.2.1. Hypothesis 1 – All white versus mixed light transitions

The primary results regarding the effect of coloured road lighting on object detection, showed that white-to-white light transitions indeed a shorter response time (i.e. a better visual performance) compared to mixed transitions, at both light levels. The response times were shorter for every mixed transition, many of which to a statistically significant extent. This was not surprising, as white light is the most common and natural light to be adapted to, and requires little other adaptation than to the intensity. For coloured transitions there is also chromatic adaptation, a change in colour space that requires additional time. People also have no experience with object detection in an environment with coloured light, leading to longer response times.

4.2.2. Hypothesis 2 – Direction of mixed light transitions

For the mixed light transitions, more distinctions in performance were predicted between the directions in which light was presented. It was expected that white light would give the lowest response times in general, and thus the assumption was that transitions towards white would perform better compared to transitions towards coloured light. Indeed, results showed that conditions in which the light transitioned towards white (e.g. red-to-white, blue-to-white etc.) had significant shorter response times compared to transitions ending with coloured light (e.g. white-to-red, white-to-blue etc.). The variety in response
times between transitions ending on white was smaller as well, suggesting that it was less relevant what colour the transition comes from. This makes sense, as the largest part of colour adaptation takes place between 40 – 70 ms (Rinner, 2000; Fairchild, 2005). Thus the first colour in the light transition does not influences the second colour that much. The fact that transitions towards coloured light have larger differences in response time did not mean that the adaptation to the first stage of the transition in the glasses had failed. A comparison between all colour-to-white transitions clearly indicated that there do exist differences in response times due to different adaptation colours. However, these effects are much smaller (e.g. a maximum of 280 ms difference in response times in the high light level condition) compared to the hundreds of milliseconds difference in response times found between the transitions which ended with coloured light. This effect was found under both high and low light level conditions. The final light colour in which objects had to be detected was therefore more important than the preceding colour in the transition.

4.2.3. Hypothesis 3 – Blue based light transitions

A more specific example of the directional effect was visible with the results of the transitions which included a blue light colour. Despite the fact that blue was expected to be a poor light colour to use in general (leading to long response times), the previous section described that there was a minimal detrimental effect on response times in transitions from blue-to-white compared to white-to-white. So although this hypothesis predicted that all transitions including blue light (whether it was from or towards blue) would show longer response times, mainly transitions towards blue performed exceptionally poor. The response times for blue light transitions were significantly longer compared to the other colours, but especially in the direction white-to-blue. Both the experimental objective results, subjective results, misses for the blue light colour, and comparison with other research confirmed that blue light is a poor colour for foveal object detection (Van Creveld, 1999). These findings are related to the fact that only a small amount of the cones is sensitive to blue, and they are scarcely found in the centre of the fovea. According to Eastman (as cited in Terry & Gibbons, 2011), this results in a very limited sensitivity for very small objects, also called small-target tritanopia. The previous section more or less concluded that the colour difference of the transition is not the largest factor of influence, but rather the ending light colour in which object detection is measured. These results further confirm this conclusion, and also uphold the detrimental effects that were predicted for blue light. Current real-life situations in which blue light is already, or will be implemented, are therefore strongly discouraged and hopefully reconsidered.

4.2.4. Hypothesis 4 – Experimental full-colour light transitions

As this was an experiment, there were two transition colour combinations included that were not related to practical real-life situations (i.e. blue-to-red and red-to-blue). These transitions should theoretically trigger the largest effects, as blue and red are two extremes in the visible spectrum (Eloholma et al., 2006) and on different cardinal axes in the opponent colour theory (Fairchild, 2005). As detection of small changes in colour is highest for colours that have already been adapted to, colours on the other cardinal axes should give the largest detrimental results (Krauskopf & Gegenfurtner, 1992; Shapiro & Zaidi, 1992). However, for the grey objects in the coloured transitions, luminance contrast plays a larger role in object detection, but the visual system also has to adapt to the new colour. This is why the largest negative influence on response times was expect with these extreme colours. The fact that the results show that blue-red transitions did not produce the most extreme effects that were expected, must still be considered with care. The reason that both these transitions had many misses is worth mentioning, because this not only proves the bad visibility in these lighting transitions, but also limits the statistical power. If the results would be replicated with less misses and still support the current results (longer
response times for white-to-blue compared to red-to-blue transitions), a possible explanation might be
the Helmholtz-Kohlrausch effect. The difference in brightness perception for red and blue light is at
equal luminance quite similar according to this effect, while the perception between blue and white
differs with a factor two. The difference between the latter in a light transition might therefore be larger
and requiring more adaptation, leading to the longer response times. To confirm whether there is indeed
a direct link between the Helmholtz-Kohlrausch effect and longer response times due to adaptation,
would require additional research.

However, for now it can be concluded that full coloured light transitions (e.g. blue-to-red) are not
necessarily worse for visibility, compared to any other mixed transition (e.g. white-to-red). For practical
implementations of these transitions in road lighting, which currently do not exist yet, the adaptation
colour or transition itself will not be the biggest problem. The main focus should be on the performance
under the final colour of light.

In hindsight, as results from hypotheses two and three showed that the transition on which a colour
ended was more important than the adaptation or transition itself, these results would probably have led
to an adjustment of the original experimental hypothesis. As transitions ending with blue light (i.e.
white-to-blue) had clearly the longest response times, and with the adaptation light colour being of less
influence, the experimental transition (blue-to-red) could never be expected to be the worst. Only the
experimental transition ending with blue (i.e. red-to-blue), could possibly have a more detrimental
effect on visual performance compared to the white-to-blue transition. In the end, however, results
showed that white-to-blue transitions still gave longer response times than the special red-to-blue
transitions.

4.2.5. Hypothesis 5 – High versus low light level transitions

The fifth hypothesis stated that higher luminance levels would improve the visual performance in
coloured light, leading to shorter response times. Besides the variation in stimuli colour, the transitions
were therefore compared on two different light levels. The purpose of testing performance under two
light intensities was to cover more of the mesopic range, but also to test whether more light would
benefit visual performance in some colours more than others. Although there is more rod than cone
sensitivity at lower light levels, the lowest light level used in this experiment was above the luminous
efficiency function threshold V(\lambda) for photopic (i.e. colour) vision (He et al., 1997). Contrary to
expectations, a group comparison between all the high and low light level transitions indicated
significantly worse response times in the high light level condition. A separate analysis for each
individual transition revealed a similar significant finding. This is surprising, as more light generally
always leads to better visibility. The findings can therefore not confirm the trend in other research, such
as by Alferdinck (2006), in which lower light level conditions are expected to require longer gaze,
increase response times and decrease vision in general. It must be noted that even though the
illuminance was higher in the high light level, due to a large difference in object position (distance to
the pole), the object had a higher luminance in the low light condition for red and amber (Appendix B).
This was due to the fact that the main focus was on creating equal visibility levels over all light levels
and transitions. Still, this finding would only explain the significant difference between light levels
found for red light, not for the other transitions. The reason that no difference of visual performance in
the expected direction were found could also indicate that there was too little difference in the two
luminance levels that were used during this experiment. Although overall, even though these results are
exceptional and cannot be fully explained, they do not change the outcome regarding the detrimental
effect of coloured light itself.
4.2.6. Hypothesis 6 – Correlation of subjective and objective measures

For some road applications the quality of light was previously evaluated with subjective judgements (Steg et al., 2010; Provincie Gelderland, 2013). Because different colours have large discrepancies in brightness perception, an object could be perceived differently under conditions that are actually similar in light level. As people have no experience with visibility effects in these different light colours, it was expected that under coloured lighting, there would not be an accurate correlation between the objective and subjective measures. Although Janoff (1989) argued in his paper that a direct link did exists between the two, no convincing evidence for such a correlation was found in the current experiment. Of all possible correlations between every light transition’s subjective rating and its objective response time, only a single correlation was found to be significant (white-to-amber). In other words, it seems confirmed that people are not able to accurately predict the visibility of an object in coloured light, even though analysis of subjective ratings often confirmed the conclusions that were based on the results which were found by analysis of the objective response times.

However, additionally, the relation between these subjective and objective measures were also analysed for each participant individually. This analysis did show multiple significant correlations between the two measures. Plotting these subjective and objective measures did indeed seem to show a link between the two (Appendix G), but the deviations from the trendline were large with hundreds of milliseconds. Unfortunately, this link’s rough prediction of visual performance is therefore too far removed from use as a reliable predictor for assessing visibility and safe traffic conditions on public roads. Finding no accurate link between the objective and subjective measures is in line with what Van Creveld (1999) found. Janoff’s (1989) predicted direct relationship between the measures still stands too though, however probably only for white-like light, as he tested in his experiment with white and yellowish HPS, MHN and MHS lighting. A significant correlation for the white-to-amber transition and relatively high correlation between white-to-white response times and ratings in current experiments data, more or less confirms the link he claims as well.

4.3. Specific colour effects

The specific colour effects section of the discussion is based on observations of the results from the perspective of each individual colour. It is separate from the main hypotheses and can therefore be seen as exploratory.

4.3.1. Red

Part of the reason for conducting this experiment was to see the relative visual performance differences (i.e. response times) for visibility in the coloured lighting used outdoors. For example, a particular finding when taking a more specific look at the differences in median response times, was the large difference between high and low light levels for transitions ending with red (Figure 5). This was the only inconsistent case that was thought to be caused by the position, even though the visibility for objects on different places was measured to be the same. A few participants (2 or 3) responded slightly surprised when they found out that the object during the red high light level condition was placed a little further to the right side. They mentioned this was just outside the area participants expected the object to appear, which was therefore the most likely reason why these response times differed so much with respect to the low light conditions. It was expected that transitions ending with red would not show other differences in response times between the light levels compared to the other transitions. Therefore, if this transition would be given the average difference from the other colours between the different
light levels, red would become the best performing transition with colour. As the relative population of L, M and S cones in the retina is somewhere between a 12:6:1 and 40:20:1 ratio (Fairchild, 2005), it is not completely surprising that this colour performs well in foveal tasks. Red cones are widely spread over the fovea and thereby also allow, in contrast to blue light, to see sharp when trying to focus in darker environments. These results are, however, not in line with what was found in some other research. For example, Alferdinck (2006) concluded on the basis of driving simulator tests red lighting to be the worst option compared to other light (white, yellow, blue). However, his experiment found these effects mostly at very low luminance levels (i.e. 0.01 cd/m²), and at larger eccentricities of five degrees and more (i.e. periphery). Other research used these larger eccentricities as well (Bullough and Rea, 2000; Akashi and Rea, 2002; Lingard and Rea, 2002), which gave red light a large disadvantage (low S/P-ratio) over blue light (high S/P-ratio). After all, blue performs better in the periphery compared to foveal tasks, as its cones are almost completely absent in the fovea (Fairchild, 2005). It also profits from the Purkinje shift in low light conditions. These experiments therefore answer different parts of the questions about visual performance with coloured road lighting; namely foveal versus peripheral vision. As for the practical application of red light on roads, if the assumptions regarding similar differences in response times for high and low light levels as in other colours are true, red can be considered the best colour option after white light. This does not mean that the differences between red and white are negligible, and implementation should therefore only take place after careful consideration.

4.3.2. Green

For the transitions ending with the mixed green colour, a very consistent objective performance was observed. Although the light colour performance rarely stood out in anything, it was always amongst the better performing transitions. The subjective ratings confirmed green, white, red (and sometimes amber), to be the better ones as well. The ratings for these colours were very similar in both light level conditions, and the ratings for the remaining colour (blue) is considerably worse. A similar order colours of visual performance is observed by Van Creveld (1999) who found that green, and especially red light allow people to perform relatively well in foveal tasks (e.g. Schnellen chart) compared to blue, and are therefore seen as the next best option after regular white light. However, if the green road lighting is implemented for energy efficiency reasons only, there are some doubts about the effectiveness. Although green LEDs currently have a high lm/W value compared to other colours, it can not be concluded that the same practical visibility is achieved as with regular white lighting. Therefore, the large advantages for green light that have been claimed in favour of other colours, seem mostly based on theoretical models rather than empirical evidence. In practice, green lighting levels might have to be increased to create a similar visual performance that of white light, hereby possibly losing the advantage of a higher efficiency for which the light was implemented. The efficiency further drops as red LEDs are often mixed with the green luminaires as well, to increase colour discrimination. As the red LEDs have a lower lm/W value, the efficiency advantage for the luminaire goes further down. An experiment linking the energy efficiency to objectively measured practical visibility would therefore be an excellent topic for further research.

4.3.3. Blue

Expectations regarding people’s performance in blue light were low from the start of the experiment. As the blue sensitive cones are mostly present on the edge of the fovea, they only lead to better vision in the periphery at lower luminances (due to the Purkinje shift, a higher S/P-ratio). However, peripheral vision was not needed for the object detection task in this experiment, also because most road lighting is designed for foveal vision (see section 1.1.5). Based on the results, the visual performance under blue
light was indeed considered to be very poor, as it resulted in the longest response times, lowest subjective ratings, and the highest amount of misses.

That blue light is in general inferior for foveal vision was found in Van Creveld’s (1999) research with Schnellen charts too, even though the participants’ subjective preference ratings for blue light were high. Van Creveld also mentioned that people’s perception of coloured light shows large discrepancies in required light level compared to white light (Helmholtz-Kohlrausch effect). In other words, more white light is needed to perceive it as equally bright as coloured lighting. Since this is especially so for blue light (Wood, 2012; Nayatani, 1997), brightness perceptions might be high while actual detection performance is low. This could lead to a dangerous overestimation of visibility and one’s safety on public roads. To some extent this was also noticed during this experiment, as some participants mentioned an increased light level for blue during transitions, when in fact nothing but the colour had changed. Other possible detrimental effects, like yellowish lenses due to ageing, could be ruled out because of the young participant sample (range was 23-31 years). Thus, due to the substantial risks and detrimental effects, there is little reason to use blue road lighting in any road situation if safety is of any concern.

4.3.4. Amber

The amber colour light transitions were included in the experiment as this is the most encountered light colour in traffic lighting worldwide. However, due to its familiarity this could also bias the subjective ratings participants had to give. The ratings given for the perceived visibility under this light colour were both the highest and the lowest in the high and low light condition respectively, and thus provided little insight. White-to-amber did end up as the only transition that had a significant correlation between rating and response time, which could again be related to experience and familiarity. As full white transitions were close to a significant correlation as well, it can be concluded that the link Janoff (1989) found between these measures is more or less confirmed.

Overall, the amber light condition does not stand out in any of the analyses, although on response times the light transition performed quite well and was close to the short scores that were observed in the white light transitions. The extent to which this is influenced by familiarity with this colour of lighting is difficult to say, which makes it hard to give it a definitive judgement. It is possible that a learning curve causes other colours to perform similarly after longer periods of time as well.

4.4. Limitations and recommendations

Spatial Radiation Pattern
The LEDs installed in the experimental setup were from the same type as used in real road luminaires. However, there was a difference in the light distribution between the colours used on the model road. This difference was caused by the angular displacement of the spatial radiation patterns between the coloured LEDs. In other words, the relative intensity of the light at the largest angle differed between colours, for example between the blue and the red light. This resulted in different illumination of the road on the side opposite to the lamppost. The effect was visible on the road and was larger than expected. This problem was largely solved by placing the objects closer to the luminaires, where the differences between the light distributions of the differently coloured LEDs were less emphasized. To create equal conditions, the object and light combinations were measured with a luminance camera, and corrected by placing the objects in slightly different positions for the different colour conditions. In following research however, it is recommended to carefully match the light distributions between
colours in advance. This could be done by slightly tilting the luminaires, or changing the placement of the lens. A raster could be used to better match the different light distributions.

**Position and performance**

Related to light distributions was the positioning of object. Due to both the difference in spatial radiation pattern as mentioned above, and to counter participant’s expectation about where the objects would appear, the positions were varied for different colours. There were two participants who made remarks about the positions of these objects. They indicated that the middle of the road is the place on which these participants said they would focus first, after which they would start looking more to the sides. This could increase the detection time, which could have been the reason why transitions ending with red had large differences between the high and low light conditions. These objects were positioned the furthest from the middle in a high red light condition, although multiple participants mentioned that the light condition offered better visibility than expected. On the other hand, in the high light level condition, objects under blue light were placed in the middle of the road, but still had a lot of misses. It is therefore difficult to directly relate positions to deviations in the measured performance. Object were not systematically and similarly placed under the different light levels.

Furthermore, as could be seen in section 2.1, luminaires were only mounted around the distance where the objects were placed for the test, instead of all along the road model. Although this would probably not affect the interpretation of the results a lot, a next version of the model street could include more luminaires to further optimise comparability with real-life situations.

**Scale model similarity**

By using a model street as experimental setup for this test, everything around it had to be on scale too. Although this was done with great care, there are some factors of which the influence cannot be fully estimated. For example, although the distance, height, objects, luminaires and light angles were all exactly at 1:20 scale, the participant’s eyes were not. Similarly, real road luminaires consist of hundreds of LEDs and lenses, where the model only used a single LED with lens. Possible differences in glare are therefore something to keep in mind, as glare impact was not considered in this study.

Other up- as well as downsides to this scale model are that the model offers limited driving realism and dynamics due to a lack of car-like movement. This also means that there are no distracting secondary tasks that could occur while driving in a natural setting (e.g. unexpected movements, signalling, other car headlights, landscape views, phone/radio, etc.). Other studies with similarities in their experimental setup included other variables relevant in real driving situations, such as light type, clothing and coloured objects (Terry and Gibbons, 2011), or eccentricity in target detection (Mayeur, Brémond & Bastien, 2008). To present users with a variety of different situations, photographs could also have conveyed statistically similar lighting perceptions as in reality, although they are not easy to manipulate (Engelke, Stokkermans & Murdoch, 2013). Renderings and animations could also come close, but the ranges of light are hard to convey digitally, especially in lit outdoor situations during night conditions. But even if all the variety and secondary tasks could be included, there is currently no way to create a single representative model of a standard cognitive load for driving that could be used to represent all traffic situations. Although coloured light is likely to hinder object detection in most situations, the extent to which coloured light influences the visibility therefore depends on the context.
Eye behaviour

The experiment made use of glasses with shutters that would open automatically. This method was chosen so that participants would not physically have to move between different models, and it allowed the researcher to place and remove objects without the participant’s knowledge. However, a downside to this method was that after each opening of the glasses, the participant had to refocus from a couple of centimetres, to a distance of over four meters. Although this is the same for all participants over all conditions, it could pose a small difference compared to real-life situations, where the change in focus would be less extreme. For future research, a polarized glass plate in front of the objects in combination with polarized shutter glasses could be an option to solve this problem.

Furthermore, it should be taken into account that although participants did the Schnellen acuity test, this does not give any information about eye defects or visual capabilities at night. It also does not guarantee good contrast sensitivities to see depth (Heiting, 2014).

Variety of the objects

The execution of this experiment was done with a small grey object used in every condition. The disadvantage of this is that the effect of object colour was not taken into account. Research by Terry and Gibbons (2011) found that under conventional light with different CCT’s, coloured objects (i.e. blue, green, red) required less luminance contrast to be detected than grey objects. In other words, colour contrast did positively influence object visibility separately from luminance contrast, up to around 50%. Because the visibility of coloured objects is completely different under each colour of light, they pose especially in these new lighting situations an additional risk for object detection. After all, a red traffic sign might be almost invisible in blue-only lighting. The fixed grey object in this experiment did not give any insights on this colour effect. However, similar arguments about variety can be made for object shapes on different levels of recognisability. The testing of frequently encountered, different shaped and coloured objects under different coloured lighting might therefore be a recommendable option for additional insight in follow-up research.

Other perspectives

Depending on the research goals, there are some other possible perspectives on the subject of visibility and road lighting that would highlight visual performance. For example, it could be an interesting option to adjust all the coloured lighting to similar perceptual brightness for the different spectra, to see how this influences the visual performance. Visual performance could also be linked to optimise road lighting efficiency by measuring energy usage for different LED spectra, when the visibility of objects is measured and tested to be exactly the same. This could provide more insight in whether the energy saving claims in favour of any light colour (e.g. green) are in fact warranted in practice.
4.5. Conclusion

This study seems to be among one of the first in investigating the influence of coloured road lighting in a practical manner. Compared to existing research it tried to increase environmental validity by using natural incidence of light instead of simulated lighting (Alferdinck, 2006) and get closer to a practical context and implementation instead of more fundamental research (Van Creveld, 1999). The current experiment hereby filled the gap in theoretical research with the practical implications of coloured lighting in a road setting. As this study is a first research contribution in the trend of coloured road lighting, the true value of this explorative contribution can only be assessed as more research reproduces similar results.

Perhaps one question that remains to be addressed was whether coloured road lighting is something that could or should be applied on real life roads. Unfortunately, the answers to this question is not as obvious as it seems. Coloured light did give lower subjective ratings and longer objective response times, and thus did negatively affect what can be seen under mesopic conditions at night. Not only did the different colour transitions differ to a statistically significant extent, but differences were at times sufficiently large to have practical consequences in visual performance as well. For the current implementation of green or red light on (mostly) country roads, this means that there is indeed added disturbance, expressed in longer response times. The analysis of median response times showed that it could more than double from 845 ms for low white-to-white to 1880 ms in low white-to-blue light transitions. To put this into perspective; if all drivers would behave and actually drive within the 50 km/h speed limit on an urban street, the distances till a full stop would be 30.28 meters (for the 845 ms response time) and 44.66 meters (for the 1880 ms response time). This is a 47% increase in stopping distance, and could have enormous implications for accident rates in urban areas. Compared to median white-to-white (845 ms, 30.28m) transitions, also white-to-red (980 ms = 32.16m, +6%) and white-to-green (1015 ms = 32.65m, +8%) transitions slowed down response time which could lead to dangerous situations. The amount of data gathered in this experiment is too limited to simply base all existing real-life lighting implementations on, and the influence in practical situations is hard to determine. However, what increases would be acceptable for a situation can be up for debate, but that coloured light would positively influence object detection and perform equally or better than regular white light, seems to be debunked. The fact that people are not directly able to accurately predict how well they see objects on the road does not help either, and could lead to dangerous misjudgements while driving. Nonetheless, subjective measures may still be important to take into consideration, as they might have influence on feelings of control, confidence and driving ability for some users when assessing road situations ahead. But as a whole, real-life road lighting implementation must have well-founded reasons to allow for the additional risks that could possibly be taken when using coloured light. Applying colour lighting on public roads for reasons that are not primarily related to the safety of its users (e.g. aesthetics, art) should be done with great caution and probably first be empirically tested more.

Seeing it all in a larger perspective, there are many more other variables on public roads which were not part of this study and which effects should be explored further. After all, it should be clear that using only one specific type of object limits the prediction of visual performance for all different traffic situations. This experiment contributed to existing research in that it gives a better sense of how large the influence of practical implementations of different coloured light sources are for object visibility and related road safety. As it seems unlikely that all varying environmental factors will ever be combined in one study while also kept strictly under control, different aspects should get highlighted in the future, one-by-one, to slowly come closer to an optimised road situation for everybody.
5. References


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6. Appendices

6.1. Appendix A

Table 10 – Experiment LED types and specifications
Types, series and frequency of the LEDs mounted on the model street.

<table>
<thead>
<tr>
<th>Brand</th>
<th>Colour</th>
<th>Series</th>
<th>Type</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>LumiLED’s</td>
<td>Red-Orange</td>
<td>LUXEON Rebel ES Color</td>
<td>LXM2-PH01-0070</td>
<td>617 nm</td>
</tr>
<tr>
<td></td>
<td>Green</td>
<td>LUXEON Rebel ES Color</td>
<td>LXML-PM01-0100</td>
<td>530 nm</td>
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<td>LumiLED’s</td>
<td>Blue</td>
<td>LUXEON Rebel ES Color</td>
<td>LXML-PB01-0023</td>
<td>470 nm</td>
</tr>
<tr>
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<td>Amber</td>
<td>LUXEON Rebel ES Color</td>
<td>LXML-PL01-0060</td>
<td>590 nm</td>
</tr>
<tr>
<td>LumiLED’s</td>
<td>White</td>
<td>LUXEON REBEL</td>
<td>LXM8-PW30</td>
<td>3050 Kelvin</td>
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</table>

*Note: The green colour used in this experiment was a combination of red-orange and green, as described in section 2.3.2.*

Spectra of the LEDs mentioned in Table 11.
6.2. Appendix B

Table 11. Object light conditions

<table>
<thead>
<tr>
<th>Light level</th>
<th>Colour</th>
<th>Background</th>
<th>Object</th>
<th>Ratio</th>
<th>VL</th>
</tr>
</thead>
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<td>High</td>
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<td>0.05263</td>
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<td>0.6799</td>
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6.3. Appendix C

Overview of experimental setup.
6.4. Appendix D

Adaptation and shutter glasses.
6.5. Appendix E

Detailed overview of response times per light transition.
6.6. Appendix F

Correlation between subjective and objective measures for top three and bottom three participants.

High correlation RT and ratings (Part. 5)

High correlation RT and Ratings (Part. 16)

High correlation RT and ratings (Part. 21)

Low correlation RT and Ratings (Part. 3)

Low correlation RT and ratings (Part. 17)

Low correlation RT and Ratings (Part. 12)
6.7. Appendix G

Plotted correlations of all subjective ratings and objective response times
*With trendline.*

\[ y = -152.47x + 1805.7 \]

\[ R^2 = 0.17913 \]
6.8. Appendix H

Information letter and informed consent.

INFORMATION LETTER

Visual Road Performance

Volunteer

Thank you for participating in this experiment.

The following steps will describe the process;

1. You will be positioned on a chair, with glasses on. Make sure to be comfortable.

2. When the glasses close, you will be adapting to light in the glasses for 90 seconds.

3. Around ten seconds before this time has passed, you will be told the glasses are about to open. You will put your right foot down on the throttle and your chin on the placeholder, ready to respond.

4. When the glasses open a couple of seconds later, you will look down the street. On this street an object may be positioned. It is your job to respond as quickly as possible, by braking with the same right foot, ONLY if you see an object on the road. It could happen that NO object is present, which means you do not have to brake.

5. After you used the brake, you give a rating on how good or bad you think the visibility of this object is with a number between 1 (invisible, cannot see anything) and 10 (perfect, could never be improved). So an object with a ‘fair’ visibility would be somewhere around 5. That is, you rate how well you can see the object placed on the roadway. More light does not always equal better visibility; base your rating on how well you can see the target, not on how bright the lighting seems or what colour it is.

6. You then close the shutters simultaneously, and relax for another 90 seconds before the process will be repeated.

We will practice this process 2 times so you know how it works, and I will talk you through the process of the experiment.

In total, 24 lighting conditions will be evaluated, which should take around 50 minutes to go through.

If the glasses are uncomfortable, you can support them on the sides during the 90 second breaks. If you need to pause for any other reason, please say so in advance.

If you have any other questions, please let the experimenter know.
INFORMED CONSENT

Visual Road Performance

Volunteer

√ I have read and understood the information letter about this research project and all my questions have been answered by the responsible researcher.

√ I had sufficient time to consider my participation in this project and I am fully aware that my participation in this project is voluntarily.

√ I know that I can decide not to participate or stop my participation at any time without giving any reason for this decision.

√ I understand and agree that my personal data will be collected, used and processed, for the purposes of the research project, by the responsible researcher and other parties that are involved in the research project. The personal data to be collected may be related to my age, gender or other sensitive aspects. I understand that my directly identifying personal data (e.g. name, address) will be separated from the research data and replaced by an assigned number/code. Access to the key/link between the assigned number and my identity will be limited to the responsible researcher and might only be disclosed to regulatory authorities or ethical committees if required for reporting to the these; or in case of medical need.

√ I agree to the use of my personal data for other research and development purposes.

√ I know that I have the right to request an overview of my personal data that have been collected about me and can have it corrected or deleted.

√ I understand that any and all information related to the study, including, but not limited to, information brochures, study descriptions, prototypes, user manuals, instructions as well as information generated by myself during the study, e.g. measurement results, user feedback constitutes confidential information of Philips. I hereby agree to keep the aforesaid information confidential, use it exclusively for the purpose of my participation in the study and not to disclose such information to any third party.

√ All confidential information revealed or submitted by Philips will remain property of Philips.

√ If you want more information or have complaints about this study, you can contact: Ruben Wesselink (ruben.wesselink@philips.com) or Maurice Donners (maurice.donners@philips.com).

√ I agree to participate as a volunteer in this research project.

□ I declare to have read the consent form and agree to its content.

Name __________________________ Signature __________________________ Date ____________

Responsible researcher

I have answered all questions about the research project and discussed the meaning and scope of this informed consent and signed it in the presence of the volunteer.

Name __________________________ Signature __________________________ Date ____________