Light.Sight.Safety

Signalling
For
Automated Driving Systems
Why? - Reason for the Study

- Since autonomous driving is coming, how can light contribute?
- Can light protect drivers and vulnerable road users?
- Which role will light play?

This results in a threefold approach:

1. Module 1
   Needs of new lighting for indicating automated state: literature study

2. Module 2A
   Signaling LED-element: lighting aspects and initial experiments

3. Module 2B
   Signaling LED-element: color / position / intensity / location
# How? - Content of the Study

<table>
<thead>
<tr>
<th>Module 1</th>
<th>Module 2A</th>
<th>Module 2B</th>
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<tbody>
<tr>
<td><strong>Jun 17- Sep 17</strong></td>
<td><strong>Oct 17- Dec 17</strong></td>
<td><strong>Jan 18 – Jun 18</strong></td>
</tr>
<tr>
<td>• Literature research of:</td>
<td>• What kind of lighting functions, with which luminance / radiance / colours, in which design / form / size are needed for communication of AD state?</td>
<td>• Real-life tests on airfield &amp; town streets with prototype LED lighting configuration allowing to gauge behaviour of test subjects during both day &amp; night time (VRUs + cars)</td>
</tr>
<tr>
<td>- Concepts &amp; investigations</td>
<td>• Build-up of test system</td>
<td>• Documentation of results</td>
</tr>
<tr>
<td>- Current laws &amp; regulations of signalling devices worldwide (similarities / differences / conclusions)</td>
<td>• Initial tests with different traffic participants (VRUs)</td>
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<tr>
<td>- Traffic accident statistics</td>
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<tr>
<td>• Definition of conflict situations between AVs and other road users</td>
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</table>
What? - Outcome of the Study

Projection systems
+ Representation of unique symbols and animations
+ Unobtrusive when not in operation
+ Visibility extremely dependent on lighting conditions and road surface
+ Recognisability dependent on distance
+ High complexity (Leveling)
→ Projection can be excluded

Displays
+ Representation of unique symbols and animations
+ High color space
+ Large dimensions for high distances needed
+ Luminance of most display technologies not sufficient for outdoor use
+ Identification problems for flat angles

LED stripe
+ High intensities possible
+ Unobtrusive when not in operation
+ Easy to implement in car design
+ Low technological complexity
+ Signals possibly not as easy to understand as signals on displays
+ Danger of confusion with other signal lights

→ Because of better photometric properties and low technological complexity a LED-Stripes will be used as signal system

→ To many disadvantages
→ Possible to use as supporting system
Conclusions - Summary of the Study

• Signal
  – Need to identify AD state during both day and night, especially in unclear traffic situations, as eye contact (intuitive way of communication) will disappear: signalling will avoid confusion & increase safety
  – Animation is important
  – Instruction in signal meaning is necessary
  – Safety increased due to better assessment of situation
Conclusions - Summary of the Study

• Colour
  – Green, magenta, blue and turquoise are ranked as particularly suitable
  – Subjects under 30 prefer turquoise, subjects over 30 prefer magenta
  – CIE xy range for blue green

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<th>2</th>
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<tr>
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<td>0,4</td>
<td>0,34</td>
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</tbody>
</table>

  – Small differences in colour naming in dark and light environment
Conclusions - Summary of the Study

- **Luminance**
  - 5900 cd/m² too low for optimal perception at daylight
  - 1300 cd/m² optimum for night-time application

- **Brightness Perception**
  - No influence of location in configurations investigated
  - Ambient luminance is main factor
  - Luminance is a better indicator of brightness than luminous intensity

  - Night: 5-17 kcd/m²
  - Day: 14-33 kcd/m²
Partners

Study performed

between June 2017 and June 2018

on behalf of

by

Technische Universität Darmstadt
Light.Sight.Safety

a coalition of lighting suppliers

endeavouring to

- creating more awareness and understanding of the safety, comfort and environmental aspects of good quality automotive lighting amongst stakeholders at both public authorities and vehicle manufacturers
- sharing findings as common positions
Autonomous driving vehicles and the role of new lighting functions in the traffic space

ISAL 2017 - Podium Discussion

Drive.ai

Nissan IDS

Mercedes-Benz F015 Konzept
Motivation I
Levels of automation and inference for signal devices

- SAE level of autonomy [J3016] -
  - Level 0: No automation
  - Level 1: Driver assistance
  - Level 2: Partial automation
  - Level 3: Conditional automation
  - Level 4: High automation
  - Level 5: Full automation
Motivation II
Communication of different road-users

§1 STVO (german traffic regulations): Participating in road traffic requires constant caution and mutual respect

→ Estimation and prediction of behavior of others

- Car -
  - Active Signals
    - Gestures
    - Eye-Contact
    - Horn
    - Signal Lights
    - Engine Sound
  - Passive Signals
    - Distance
    - Speed
    - Engine Sound
    - Type of Vehicle
  - Driving Behaviour

- Pedestrians -
  - Active Signals
    - Gestures
    - Eye-Contact
    - Shout
  - Passive Signals
    - Distance
    - Speed
    - Ages
    - Clothes
  - Walking Behaviour

With AV the intuitive ways of communication disappear

Visibility
Lighting Conditions
Weather Conditions
Noise Level
Number of Road Users
Overview

- Concepts and investigations of signal devices for automated vehicles

- Laws and regulations
  - Commissions and policies
  - Standards for signal lights
  - Cultural differences

- Conflict situations of passenger cars and other road-users
  - Traffic accident statistics
  - Possible encounter situations
  - System requirements

- Summary
Concepts and investigations I
Overview

- Comparison of different concepts / studies for new signaling devices which were made over the last years

- In general 3 types of technologies

  - Display-Systems
  - Projection-modules
  - Lightstrips and additional lamps
Concepts and Investigations II
Display-systems

Semcon Smiling Car

Drive.ai

Google Pedestrian Notification

AutonoMi
Concepts and Investigations IV
Projection-Systems

Mercedes-Benz Digital Light
RISE Viktoria TII, Lightstrip

Mercedes-Benz F015 Konzept

Audi e-tron Sportback concept
Concepts and Investigation V
Lightstrips / lamps

BMW Vision Next 100

Nissan IDS

AVEC, Eindhoven University of Techn.

AVIP, Chalmers University
Concepts and investigations VI

Conclusion

<table>
<thead>
<tr>
<th>Technology</th>
<th>Position on vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displays (LCD, SMD-LED, OLED, Curved, transparent, flexible etc.)</td>
<td>door, front, rear, roof</td>
</tr>
<tr>
<td>RGB(W)-LED-lightstrips</td>
<td>rearview mirror, side, windscreen</td>
</tr>
<tr>
<td>LED-lamp</td>
<td>rims, hood</td>
</tr>
<tr>
<td>Laser-projection</td>
<td>front</td>
</tr>
<tr>
<td>LED-projection</td>
<td>Front or side of the vehicle</td>
</tr>
</tbody>
</table>

- Almost every concept realized with light-based solutions
- Wide range of suggested technological concepts
- Only one conflict situation regarded (crossing)

**Conclusion**

1. Are there more conflict situations besides crossing?
2. What are the needed photometric requirements?
3. Which technologies should be used?
Laws and regulations I
Commissions and policies

„...the technology must be designed in such a way that critical situations do not arise in the first place... the entire spectrum of technological options – ... signals for persons at risk, ... – should be used and continuously evolved...”
Rule No. 5, ethics commission Automated and connected driving, Report June 2017, Federal Ministry of Transport and Digital Infrastructure

„...it must be possible to clearly distinguish whether a driverless system is being used or whether a driver retains accountability with the option of overruling the system...”
Rule No. 16, ethics commission Automated and connected driving, Report June 2017, Federal Ministry of Transport and Digital Infrastructure
Laws and regulations II
Commissions and policies

Autonomous vehicles potentially have unique needs for signaling other vehicles that they are autonomous and signaling pedestrians as to the vehicle's intent. This task force will explore these unique needs and develop recommendations for standardized solutions to meet these needs.

SAE J3134 ADS-Equipped Vehicle Signal and Marking Lights

Manufacturers and other entities should consider how HAVs will signal intentions to the environment around the vehicle, including pedestrians, bicyclists, and other vehicles...

Chapter 5, Federal Automated Vehicles Policy, September 2016, National Highway Traffic Safety Administration
Laws and regulations III
Commissions and policies

A 450-page roadmap was published by SAEC (Society of Automotive Engineers of China). Officials said earlier this year the draft would be released to set out technical standards, including a common language for cars to communicate with each other and regulatory guidelines.

Laws and regulations IV
Standards

Colours of Light Signals, CIE S 004/E-2001

1. Predefined to use only red, yellow, white, green, blue and black as „no color”

2. Use only four colors for one signaling system (as used for vehicles: red, white, yellow and blue for emergency vehicles)

⇒ Adding green to the color range can be meaningful:
Research projects in the past have shown, that a system with green rear lights and red stop lights can reduce reaction time by 16 % (Mortimer 1970, Rosemann 1975)

- **Rejected because it can lead to confusion for traffic behind**
- **Usable for forward signals?**
Laws and regulations V
Cultural differences

Road Warning signs around the World

https://commons.wikimedia.org/wiki/File:Road_Warning_signs_around_the_World.svg
Conflict situations I
Traffic accident statistics

Bicycle accidents with injuries where other road-users are involved
2016\textsuperscript{1}

<table>
<thead>
<tr>
<th>Involved in accident</th>
<th>Absolut</th>
<th>Relative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>49165</td>
<td>74,5 %</td>
</tr>
<tr>
<td>Other bicycle</td>
<td>5741</td>
<td>8,7 %</td>
</tr>
<tr>
<td>Pedestrian</td>
<td>4224</td>
<td>6,4 %</td>
</tr>
<tr>
<td>Freight transport</td>
<td>6863</td>
<td>10,4 %</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>65993</strong></td>
<td><strong>100 %</strong></td>
</tr>
</tbody>
</table>

reasons are:
- „wrong road-use”
- „turning, backwards driving, approaching”
- „inappropriate speed”
- „right of way”
- „influence of alcohol”

\textsuperscript{1} Statistisches Bundesamt, Verkehrsunfälle 2016, Kraftrad- und Fahrradunfälle im Straßenverkehr

24,6 % (12095) of accidents with cars caused by cyclists

Solve with additional visual signals?
Conflict situations II
Possible encounter situations

- Car to bicycle(s)
- Car to pedestrian
- Car to pedestrians
- Car to car
Conflict situations III
System requirements

- Display of signal around the car
- Clearly defined color of signal
- No confusion with other signals
- Controllable brightness (day / night / weather)
- Detection range to the front (min. 47.25 m) and to the back (min. 25.5m)
Summary

- Intuitive way of communication especially in unclear traffic situations will disappear with automated vehicles
  - We need new signaling systems to avoid confusion and increase safety

- Define conflict situations where new signaling devices are needed
  - Based on accident statistics and first studies

- Plenty of concepts and ideas for new signaling devices
  - Definition of requirements / harmonization between SAE and ECE
Thank you for your attention!
Motivation and objectives

Communication of automated vehicles (AVs) to other road users

V2X via radio

AV to vulnerable road users (pedestrians, cyclists)?

Is there need of new signal lighting?
What is the state of technology?
What is the state of research?
## Project overview

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<td>Studies at day- and night-time</td>
<td>Systematic investigation of factors</td>
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<tr>
<td>Accident statistics</td>
<td>First Studies</td>
<td>Real traffic</td>
<td>Laboratory studies</td>
</tr>
</tbody>
</table>

**June 17**

LSS project: needs of new lighting for indicating automated state

**September 17**

**December 17**

**April 18**

07.12.2017 | Technische Universität Darmstadt | Fachgebiet Lichttechnik | Dmitrij Polin | 31
Module 2A

Objectives

- Analysis of use cases and test design ✓
- Conceptual design and implementation of the lighting ✓
- First studies ✓
Analysis of use cases
Causer of accidents

- car
- bicycle
- motorcycle
- goods vehicle
- pedestrian
Analysis of use cases
Causes of accidents in relation to cyclists

- ignoring traffic regulations
- insufficient safety distance
- entering the flow traffic
- getting in / out the car
- ignoring right of way
- wrong turning

Important use case for investigation!

Quelle: Verkehrssicherheitslage 2016, Polizei Berlin
Analysis of use cases
Example: Eye contact cyclist in the roundabout

Roundabout in Berlin with most bicycle accidents
Analysis of use cases
Injured cyclists in 2016

Accidents by lighting conditions
- Daylight: 80%
- Dusk: 5%
- Darkness: 15%

Investigation at daylight
Concept and Implementation of the signal lighting

- Communication: AV to cyclist
- Position of lighting: clearly visible → roof, 360°
- Stripes with 144 RGBW-LEDs
- Only for investigation → no proposal for implementation / regulation
Signal Lighting

In the investigation $L = 5900 \text{ cd/m}^2$ of all examined colors
First Investigation at day time
Test design

<table>
<thead>
<tr>
<th>Familiarisation</th>
<th>Examination 1</th>
<th>Examination 2 stationary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject on the bike</td>
<td>Subject on the bike</td>
<td>Subject standing</td>
</tr>
<tr>
<td>• straight ahead</td>
<td>• straight ahead</td>
<td>• standing</td>
</tr>
<tr>
<td>• max 15 km/h</td>
<td>• max 15 km/h</td>
<td>• 5 m to the test vehicle</td>
</tr>
<tr>
<td>Test vehicle</td>
<td>Test vehicle</td>
<td>Test vehicle standing</td>
</tr>
<tr>
<td>• overtaking and bending</td>
<td>• overtaking but not bending</td>
<td>• Direction indicator is activated</td>
</tr>
<tr>
<td>• Direction indicator is activated</td>
<td>• Direction indicator is activated</td>
<td>• Additional signal is activated</td>
</tr>
<tr>
<td>• Additional signal is deactivated</td>
<td>• Additional signal is activated</td>
<td>• Variation of signal colors</td>
</tr>
</tbody>
</table>

Colors in a random order
- Green
- Amber
- White
- Turquoise
First investigation
Example of the procedure
First investigation
Results: Is the novel light signal perceived when cycling?

23 naive subjects
- 2 female, 21 male
- Aged between 21 and 33 years

Possible reasons why it was not perceived
- Complex situation
- Focusing on car behavior
- High ambient luminance
- Low luminance of the light signal
- Low contrast to the car color (white)
First investigation
Results: Luminance

$L_{\text{stripe}} \approx 5900 \text{ cd/m}^2$

$L_{\text{vehicle}} \approx 1800 \text{ cd/m}^2 \Rightarrow C = 2.28$

$L_{\text{road}} \approx 620 \text{ cd/m}^2 \Rightarrow C = 8.51$

$L_{\text{sky}} \approx 2050 \text{ cd/m}^2 \Rightarrow C = 1.88$
First investigation
Results: white light signal $\rightarrow$ low contrast to white car
First investigation
Results: which color is most suitable?

- **green**
  - "Stands for security and positivity"
  - "Good visibility"
  - "No mix-up with other vehicle lights"
- **Magenta**
  - "Good visibility"
  - "No mix-up with other vehicle lights"
- **Blue**
  - "Blue LEDs represent technology"

Multiple answers possible

- green - 65%
- magenta - 39%
- blue - 30%
- turquoise - 13%
- amber - 9%
- yellow - 9%
- red - 4%

Comments of subjects:

- green
- Magenta
- Blau
First investigation

Conclusion

- Special signaling in automated vehicles is desired
- Increased safety due to better assessment of the situation
- Previous instruction in signal meaning necessary
- Green, magenta, blue and turquoise are ranked as particularly suitable
- 5900 cd/m² is too low for optimal perception at daylight
Second investigation
Test design

**Examination 1**
Subject on the bike
- straight ahead
Test vehicle
- overtaking but not bending
- Direction indicator is activated
- Additional signal is activated
- Only magenta chaser light

**Examination 2 stationary**
Subject **standing**
- 5 m to the test vehicle
- Evaluation different colors
Test vehicle **standing**
- Direction indicator is activated
- Additional signal is activated
- Variation of signal colors

$L_{\text{stripe}} = 1300 \text{ cd/m}^2$
$T_{\text{on}} = 500 \text{ ms}$
$T_{\text{off}} = 1000 \text{ ms}$
Second investigation
Example of the procedure
Second investigation

Subjects

39 persons
- On bike: 8 persons
- Stationary: 31 persons

Aged from 20 to 73 years
- Mean age 33 years
- 24 persons under 30 years
- 15 persons over 30 years
Second investigation
How often do you cycle ...

... when it is light?

... when it is dark?
Second investigation
Evaluation of the use case

How often have you experienced the situation as a cyclist?

- Rarely: 4
- Often: 12

How do you judge this situation?

- Not dangerous: 10
- Very dangerous: 20
Second investigation
Additional signal light

Do you think an additional light signal is useful?

---

Not useful | Useful
---|---
2 | 12
4 | 10
6 | 8
8 | 6
10 | 4
12 | 2

fully applies
largely applies
partially applies
does rather not apply
does not apply at all

permanent | chaser | blinking
Second investigation
Results: Which of the colors do you find most suitable?

- 8 persons: Color does not matter
- Much more important is the animation
- Animation must be intuitively understandable

Mean values:
- under 30: prefer turquoise and blue
- over 30: prefer magenta

Persons under 30 prefer turquoise and blue.
Persons over 30 prefer magenta.
Second investigation
A possible influence on color perception

![Graph showing transmittance or relative intensity for different age groups.](image)

- Red line: 20 years
- Green line: 32 years
- Blue line: 58 years
Second investigation
Optimal luminance of magenta chaser light

- 11 of 39 subjects
- Stationary 5 m to the car
- Direction indicator is activated
- Magenta chaser light
- 7 dimming levels → optimal luminance?
Conclusion of Modules 1 and 2A

- Special signaling in automated vehicles is desired → Animation is important
- Increased safety due to better assessment of the situation
- Previous instruction in signal meaning necessary
- Green, magenta, blue and turquoise are ranked as particularly suitable at daylight
- 5900 cd/m² to low for optimal perception at daylight
- Luminance about 1300 cd/m² optimum for nighttime application
- Subjects over 30 prefer magenta
- Subjects under 30 prefer turquoise
Project overview

Module 1
- Literature research
- Determination and analysis of conflict situations

Module 2A
- Conceptual design
- Development of lighting
- First Studies

Module 2B
- Selection of some factors
- Studies at day- and night-time
- Real traffic

Module X
- Elaboration and establishment of a basis for regulations
  - Systematic investigation of factors
  - Laboratory studies
  - Field studies
  - Online survey
  - Development of proposals and recommendations

Juni 17 | September 17 | December 17 | April 18

LSS project: needs of new lighting for indicating automated state
Module 2B

Objectives
- Indicating self driving cars
- Communication to other road users

Details
- Selection of some factors
  - Color
  - Luminance
  - Position
- Studies at day- and night-time
- Real traffic situations
- Observers: driver, pedestrians, cyclists

Next steps
- Studies on public roads
- New lighting systems for daytime studies
- Studies with the new lighting system
Next steps in Module 2B
Parameters and factors of novel lighting

- Ambient light
- Color
- Position
- Luminance
- Shape
- Contrast
- Timing
- Animation

- Driving situation
- Vehicle dynamic
- Weather
- Road users
- Infrastructure
Share of the population under 15 and over 64 years of age in the world's regions in 2017

- Africa: 41% Under 15 years, 3% Over 64 years
- Latin America: 26% Under 15 years, 8% Over 64 years
- Worldwide: 26% Under 15 years, 9% Over 64 years
- Asia: 24% Under 15 years, 8% Over 64 years
- Australia, Oceania: 23% Under 15 years, 12% Over 64 years
- North America: 19% Under 15 years, 15% Over 64 years
- Europe: 16% Under 15 years, 18% Over 64 years
Demographic development in Germany
Share of senior citizens in the population and accidents 2014

Examination of elderly people is especially important!
Thank you for your attention!
Second investigation
Which of the colors do you find most suitable?

under 30 years of age
Results
Which of the colors do you find most suitable?

over 30 yeas of age
LSS – Module 2B
Final meeting
Dmitrij Polin, TU Darmstadt, June 26
# Project overview

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<td>Turquoise xy range</td>
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<td>Development of lighting</td>
<td>First Studies</td>
<td>Intensity day / night</td>
<td>Location</td>
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<tr>
<td></td>
<td></td>
<td>Influence of animations</td>
<td>Communication</td>
</tr>
</tbody>
</table>

## Module 2A
- Conceptual design
- Development of lighting
- First Studies

## Module 2B
- Turquoise xy range
- Intensity day / night
- Influence of animations
- Location
- Communication

## Module X
- Intuitive interaction and Communication

- Development of intuitive signals / animations
- Systematic investigation of factors
- Laboratory studies
- Field studies
- Online survey
- Development of proposals and recommendations

### LSS project: needs of new lighting for indicating automated state

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</table>
Agenda

- Presentation of experimental results
- Demo on the car
- Demo in the lab
- Final discussion
Requirements

Color (according to CIE)
- no need to continue studying amber and green as these are already used for other traffic safety purposes
- magenta is an understandable choice but also not supported by CIE
- turquoise seems to be the preferred solution / way to go: the definition of the borders of a X/Y color field would be a major outcome of Module 2B

Intensity
- confirmation of a luminance value suitable for better vision would be a major outcome of Module 2B
- test set-up will ideally allow to confirm
- luminance value of xxxx cd/m² (> 5900) above which the visual recognition is better, or reaches a certain threshold
- different recognition thresholds for daytime and nighttime e.g. values comparable to DRL

Position
- testing to be performed in such a way that both top mounting & frontend mounting are covered
- testing to confirm other possible influencing visual factors

Communication
- the cyclist testing showed that subjects mix the interpretation of the turn indicator signal and the AD signal: a second round of tests with improved setup is needed to better distinguish which reaction of the test person relates to which signal
- setup to be split in a way to “leave” the communication topics to others and concentrate on the technical lighting part
- advice on the communication options related to existing studies is welcome (Module 1 literature studies, AVIP etc.)
Experiments

Field experiments
- Color naming
- Assessment of intensity
- Dependence of intensity on animation and color

Subjects
- 47 people at daytime
  - 29 people < 30 years, avg=23, sd=3
  - 18 people > 30 years, avg=51, sd=13
- 44 people at nighttime
  - 16 people < 30 years, avg=22, sd=3
  - 28 people > 30 years, avg=52, sd=11

Lab experiments
- Color naming
- Interpretation of Animations

Subjects
- 22 people at Color naming
  - All < 34 years, avg=25, sd=4
- 16 people at Interpretation of Animations
  - All < 35 years, avg=27, sd=3
Location of lights

RGBW LED Stripe

Retrofit
### Photometric values

#### Day

<table>
<thead>
<tr>
<th></th>
<th>$L_{\text{max}}$</th>
<th>$I_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>32</td>
<td>129</td>
</tr>
<tr>
<td>Grill, 3 rows</td>
<td>32</td>
<td>231</td>
</tr>
<tr>
<td>Grill, 2 rows</td>
<td>32</td>
<td>154</td>
</tr>
<tr>
<td>Headlamps</td>
<td>32</td>
<td>193</td>
</tr>
<tr>
<td>Retrofit DRL</td>
<td>17</td>
<td>18</td>
</tr>
</tbody>
</table>

#### Night

$L_{\text{night}} = 0.6 \times L_{\text{day}}$

Diffusor to reduce luminance at night
Experiment 1: Color naming, field test

Goal: What is turquoise?

day and night

Lights
LED stripes in grill
16 Colors in turn
Random order

Subject's task
color naming

resting car

10 m
# Experiment 1: Color naming

## Color Designation for Lights

- By Kenneth L. Kelly
- National Bureau of Standards
- Research Paper, November 1943

### Bluish Green

<table>
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<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0.0175</td>
<td>0.26</td>
<td>0.24</td>
<td>0.035</td>
</tr>
<tr>
<td>y</td>
<td>0.475</td>
<td>0.36</td>
<td>0.34</td>
<td>0.36</td>
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</tbody>
</table>

### Blue Green

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>x</td>
<td>0.035</td>
<td>0.24</td>
<td>0.22</td>
<td>0.06</td>
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<tr>
<td>y</td>
<td>0.36</td>
<td>0.34</td>
<td>0.3</td>
<td>0.24</td>
</tr>
</tbody>
</table>

### Greenish Blue

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>x</td>
<td>0.06</td>
<td>0.22</td>
<td>0.21</td>
<td>0.083</td>
</tr>
<tr>
<td>y</td>
<td>0.24</td>
<td>0.3</td>
<td>0.26</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Experiment 1: Color naming, field test
Results daytime

percentual designation

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>B</th>
<th>T</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1624</td>
<td>0.4007</td>
<td>0%</td>
<td>47%</td>
<td>53%</td>
</tr>
<tr>
<td>0.1605</td>
<td>0.3140</td>
<td>13%</td>
<td>87%</td>
<td>0%</td>
</tr>
<tr>
<td>0.1587</td>
<td>0.2325</td>
<td>77%</td>
<td>23%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Example 50% threshold

EN 12966 green

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>B</th>
<th>T</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2833</td>
<td>0.3238</td>
<td>0%</td>
<td>39%</td>
<td>61%</td>
</tr>
<tr>
<td>0.2739</td>
<td>0.3060</td>
<td>23%</td>
<td>34%</td>
<td>19%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>x</th>
<th>y</th>
<th>B</th>
<th>T</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2435</td>
<td>0.3383</td>
<td>0%</td>
<td>48%</td>
<td>52%</td>
</tr>
<tr>
<td>0.2219</td>
<td>0.3014</td>
<td>11%</td>
<td>89%</td>
<td>0%</td>
</tr>
<tr>
<td>0.2144</td>
<td>0.2622</td>
<td>61%</td>
<td>39%</td>
<td>0%</td>
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</tbody>
</table>
Experiment 1: Color naming, field test
Results nighttime

percentual designation

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>B %</th>
<th>T %</th>
<th>G %</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1724</td>
<td>.4014</td>
<td>0%</td>
<td>43%</td>
<td>57%</td>
</tr>
<tr>
<td>.1674</td>
<td>.3309</td>
<td>23%</td>
<td>77%</td>
<td>0%</td>
</tr>
<tr>
<td>.1686</td>
<td>.2524</td>
<td>47%</td>
<td>53%</td>
<td>0%</td>
</tr>
</tbody>
</table>

small differences between day and night

<table>
<thead>
<tr>
<th>X</th>
<th>Y</th>
<th>B</th>
<th>T</th>
<th>G</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>.2853</td>
<td>.3278</td>
<td>5%</td>
<td>8%</td>
<td>55%</td>
<td>32%</td>
</tr>
<tr>
<td>.2769</td>
<td>.3160</td>
<td>20%</td>
<td>32%</td>
<td>21%</td>
<td>27%</td>
</tr>
<tr>
<td>.2505</td>
<td>.3403</td>
<td>3%</td>
<td>27%</td>
<td>70%</td>
<td></td>
</tr>
<tr>
<td>.2309</td>
<td>.3134</td>
<td>13%</td>
<td>68%</td>
<td>19%</td>
<td></td>
</tr>
<tr>
<td>.2184</td>
<td>.2822</td>
<td>43%</td>
<td>47%</td>
<td>10%</td>
<td></td>
</tr>
</tbody>
</table>

EN 12966

green
Experiment 2: Color naming, lab
Experimental Setup

Light
RGBW + 494nm
$L = \text{const} = 300 \text{ cd/m}^2$
31 blue-greens in turn
31 rgbwyp in between
Random order

Subject’s task
color naming

Ambient light on / off

10 cm
10 cm
1.5 m

EN 12966
Green
Experiment 2: Color naming, lab
Results bright environment 1

\[ f_{\text{turquoise}} + f_{\text{green}} + f_{\text{blue}} = 100\% \]

Turquoise is a mix of blue and green \(\rightarrow\) between blue and green

\(\rightarrow\) Limits: 50% threshold of blue / green
Experiment 2: Color naming, lab
Results bright environment 2

\[ f_{\text{turquoise}} + f_{\text{green}} + f_{\text{blue}} = 100\% \]

Turquoise is a mix of blue and green \( \rightarrow \) between blue and green

\( \rightarrow \) Limits: 50% threshold of blue / green
Experiment 2: Color naming, lab
Results bright environment 3

\[ f_{\text{turquoise}} + f_{\text{green}} + f_{\text{blue}} = 100\% \]

Turquoise is a mix of blue and green → between blue and green

Limits: 50% threshold of blue / green
Experiment 2: Color naming, lab

Results summary

- Small differences between dark and light environment
- Similar results in lab and field
- No age-related differences
- Proposal for xy range:

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0.04</td>
<td>0.15</td>
<td>0.24</td>
<td>0.22</td>
<td>0.06</td>
</tr>
<tr>
<td>y</td>
<td>0.4</td>
<td>0.4</td>
<td>0.34</td>
<td>0.3</td>
<td>0.24</td>
</tr>
</tbody>
</table>
Requirements

Color (according to CIE)
- no need to continue studying amber and green as these are already used for other traffic safety purposes
- magenta is an understandable choice but also not supported by CIE
- turquoise seems to be the preferred solution / way to go: the definition of the borders of a X/Y color field would be a major outcome of Module 2B

Intensity
- confirmation of a luminance value suitable for better vision would be a major outcome of Module 2B
- test set-up will ideally allow to confirm
- luminance value of xxxx cd/m² (> 5900) above which the visual recognition is better, or reaches a certain threshold
- different recognition thresholds for daytime and nighttime e.g. values comparable to DRL

Position
- testing to be performed in such a way that both top mounting & frontend mounting are covered
- testing to confirm other possible influencing visual factors

Communication
- the cyclist testing showed that subjects mix the interpretation of the turn indicator signal and the AD signal: a second round of tests with improved setup is needed to better distinguish which reaction of the test person relates to which signal
- setup to be split in a way to “leave” the communication topics to others and concentrate on the technical lighting part
- advice on the communication options related to existing studies is welcome (Module 1 literature studies, AVIP etc.)
Experiment 3: Assessment of intensity

Goals: Optimal intensity range, dependence on location and color

Lights
All modules in turn
3 colors (greenish blue, green blue, bluish green)
5 intensities per module and color
day and night

Subject’s task
assessment of the brightness
dark / optimal / bright

resting car

10 m
**Experiment 3: Assessment of intensity**

**Results day, grill**

$f_{\text{dark}} + f_{\text{bright}} + f_{\text{optimal}} = 100\%$

**Optimal intensity**

in between of dark and bright

<table>
<thead>
<tr>
<th>50% thresholds</th>
<th>dark</th>
<th>bright</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative intensity</td>
<td>0.43</td>
<td>1.00</td>
</tr>
<tr>
<td>$L$ in kcd/m²</td>
<td>13.6</td>
<td>32.0</td>
</tr>
<tr>
<td>$I$ in cd</td>
<td>99.0</td>
<td>231.0</td>
</tr>
</tbody>
</table>
Experiment 3: Assessment of intensity
Results day, blue green

<table>
<thead>
<tr>
<th>Location</th>
<th>grill</th>
<th>grill small</th>
<th>headlamp</th>
<th>top</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{min}$ kcd/m²</td>
<td>14</td>
<td>14</td>
<td>16</td>
<td>13</td>
<td>14</td>
</tr>
<tr>
<td>$L_{max}$ kcd/m²</td>
<td>32</td>
<td>33</td>
<td>35</td>
<td>34</td>
<td>33</td>
</tr>
</tbody>
</table>

Similar luminance range independently from the location and luminous intensity.
Experiment 3: Assessment of intensity
Results day, color

<table>
<thead>
<tr>
<th>Luminance in cd/m²</th>
<th>bluish green</th>
<th>blue green</th>
<th>greenish blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{min}$ kcd/m²</td>
<td>12</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>$L_{max}$ kcd/m²</td>
<td>33</td>
<td>33</td>
<td>30</td>
</tr>
</tbody>
</table>
Experiment 3: Assessment of intensity
Results day, retrofit

\[ L_{\text{min}} = I_{\text{rel,50\%}} \cdot L_{\text{max}} = 0.69 \cdot 17 = 11.7 \text{ kcd/m}^2 \]

Similar luminance to the LED stripes

<table>
<thead>
<tr>
<th>stripes</th>
<th>bluish green</th>
<th>green blue</th>
<th>greenish blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{\text{min}} ) kcd/m²</td>
<td>12</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>( L_{\text{max}} ) kcd/m²</td>
<td>33</td>
<td>33</td>
<td>30</td>
</tr>
</tbody>
</table>
Experiment 3: Assessment of intensity
Results night, color

<table>
<thead>
<tr>
<th>Color</th>
<th>$L_{\text{min}}$ kcd/m²</th>
<th>$L_{\text{max}}$ kcd/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>bluish green</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>blue green</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>greenish blue</td>
<td>5</td>
<td>14</td>
</tr>
</tbody>
</table>

![Graph showing luminance in kcd/m² for different colors](image-url)
Experiment 3: Assessment of intensity
Results night, retrofit

\[
L_{\text{min}} = I_{\text{rel,50\%}} \cdot L_{\text{max}} = 0.38 \cdot 17 = 6.46 \text{ kcd/m}^2
\]

Similar luminance to the LED stripes

<table>
<thead>
<tr>
<th>Stripes</th>
<th>bluish green</th>
<th>blue green</th>
<th>greenish blue</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{\text{min}} ) kcd/m²</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>( L_{\text{max}} ) kcd/m²</td>
<td>17</td>
<td>17</td>
<td>14</td>
</tr>
</tbody>
</table>
Experiment 3: Assessment of intensity

Summary

- Low influence of location and color
- Major influence of ambient luminance
- Luminance is a better indicator of brightness than luminous intensity

### Photometric range at night
- Luminance: 5-17 kcd/m²
- Luminous intensity: max. 154 cd

### Photometric range at day
- Luminance: 14-33 kcd/m²
- Luminous intensity: max. 230 cd

### Properties of lights

<table>
<thead>
<tr>
<th></th>
<th>$L_{\text{max}}$</th>
<th>$I_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>32</td>
<td>129</td>
</tr>
<tr>
<td>Grill, 3 rows</td>
<td>32</td>
<td>231</td>
</tr>
<tr>
<td>Grill, 2 rows</td>
<td>32</td>
<td>154</td>
</tr>
<tr>
<td>Headlamps</td>
<td>32</td>
<td>193</td>
</tr>
<tr>
<td>Retrofit DRL</td>
<td>17</td>
<td>18</td>
</tr>
</tbody>
</table>

Night $L_{\text{night}} = 0.6 \times L_{\text{day}}$
Experiment 3: Assessment of intensity

Summary

![Bar chart showing intensity levels for day and night]

Proposal from SAE single range

\[I = [80, 300] \text{ cd}\]

\[L = [14, 17] \text{kcd/m}^2 \rightarrow \text{common range}\]

\[A = [4700, 21500] \text{mm}^2\]

Proposal from GTBWGSL day / night

\[I_{\text{night}} = [10, 80] \text{ cd} \quad I_{\text{day}} = [60, 260] \text{ cd}\]

\[A_{\text{night}} = [600, 16000] \text{mm}^2 \quad A_{\text{day}} = [1800, 18500] \text{mm}^2\]
**Experiment 3: Assessment of intensity**

**Examples**

<table>
<thead>
<tr>
<th>H in mm</th>
<th>W in mm</th>
<th>A in mm²</th>
<th>Lmin kcd/m²</th>
<th>Lmax kcd/m²</th>
<th>Imin cd</th>
<th>Imax cd</th>
<th>Lmin kcd/m²</th>
<th>Lmax kcd/m²</th>
<th>Imin cd</th>
<th>Imax cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>100</td>
<td>1000</td>
<td>14</td>
<td>33</td>
<td>14</td>
<td>33</td>
<td>5</td>
<td>17</td>
<td>5</td>
<td>17</td>
</tr>
<tr>
<td>10</td>
<td>200</td>
<td>2000</td>
<td>14</td>
<td>33</td>
<td>28</td>
<td>66</td>
<td>5</td>
<td>17</td>
<td>10</td>
<td>34</td>
</tr>
<tr>
<td>10</td>
<td>300</td>
<td>3000</td>
<td>14</td>
<td>33</td>
<td>42</td>
<td>99</td>
<td>5</td>
<td>17</td>
<td>15</td>
<td>51</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>2000</td>
<td>14</td>
<td>33</td>
<td>28</td>
<td>66</td>
<td>5</td>
<td>17</td>
<td>10</td>
<td>34</td>
</tr>
<tr>
<td>20</td>
<td>200</td>
<td>4000</td>
<td>14</td>
<td>33</td>
<td>56</td>
<td>132</td>
<td>5</td>
<td>17</td>
<td>20</td>
<td>68</td>
</tr>
<tr>
<td>20</td>
<td>300</td>
<td>6000</td>
<td>14</td>
<td>33</td>
<td>84</td>
<td>198</td>
<td>5</td>
<td>17</td>
<td>30</td>
<td>102</td>
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</tbody>
</table>
Experiment 4: Dependence of intensity on animation

Goals: Optimal intensity range depending on animation

Subject's task
assessment of the brightness
dark / optimal / glaring

Lights
LED stripes in grill
Animations

day and night

resting car

10 m
Experiment 4: Dependence of intensity on animation

- Location: grill
- 3 LED rows
- $L_{\text{max,animation}} = k \cdot L_{\text{max,LED}}$
- $k = [0.2, 0.4, 0.6, 0.8, 1]$
- $T = [200, 1000]\text{ms}$
- Random order

Result: no significant difference to steady light

$\Rightarrow$ no influence on brightness perception
Experiment 4: Dependence of intensity on animation

Increasing from the middle

- Location: grill
- 3 LED rows
- $L_{\text{max,animation}} = k \cdot L_{\text{max,LED}}$
- $k = [0.2, 0.4, 0.6, 0.8, 1]$
- $T = [200, 1000] \text{ms}$
- Random order

Result: no significant difference to steady light

$\Rightarrow$ no influence on brightness perception
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- advice on the communication options related to existing studies is welcome (Module 1 literature studies, AVIP etc.)
Experiment 5: Interpretation of animations

- Presentation of the animations on a monitor in the lab
- 9 Animations
- 16 people
- Evaluation in terms of
  - Comprehencibility
  - Intuitive interaction (after explanation)
### Experiment 5: Animation 1 – automated mode

Proposal of SAE

**Weighted sum → Intuitiveness = 4.3**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>No danger</th>
<th>Design</th>
<th>DRL</th>
<th>Crossing possible, I am yielding</th>
<th>Caution, I am not yielding</th>
<th>I see you</th>
<th>Automated mode</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without explanation</td>
<td>7%</td>
<td>36%</td>
<td>36%</td>
<td>0%</td>
<td>4%</td>
<td>7%</td>
<td>11%</td>
<td>0%</td>
</tr>
<tr>
<td>After explanation</td>
<td>4%</td>
<td>7%</td>
<td>11%</td>
<td>4%</td>
<td>0%</td>
<td>4%</td>
<td><strong>46%</strong></td>
<td>0%</td>
</tr>
</tbody>
</table>

Relative Frequency

![Graph showing relative frequency](image)
### Experiment 5: Animation 2 – no danger

![Image of dimming car lights](image)

**Weighted sum → Intuitiveness = 2.9**

<table>
<thead>
<tr>
<th></th>
<th>No danger</th>
<th>Design</th>
<th>DRL</th>
<th>Crossing possible, I am yielding</th>
<th>Caution, I am not yielding</th>
<th>I see you</th>
<th>Automated mode</th>
<th>O ther</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without explanation</strong></td>
<td>7%</td>
<td>21%</td>
<td>7%</td>
<td>11%</td>
<td>14%</td>
<td>7%</td>
<td>11%</td>
<td>7%</td>
</tr>
<tr>
<td><strong>After explanation</strong></td>
<td><strong>32%</strong></td>
<td>11%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td><strong>14%</strong></td>
<td>7%</td>
</tr>
</tbody>
</table>

28.06.2018 | Technische Universität Darmstadt | Fachgebiet Lichttechnik | Dmitrij Polin | 100
### Experiment 5: Animation 3 – crossing possible

**Weighted sum → Intuitiveness = 3.8**

<table>
<thead>
<tr>
<th></th>
<th>No danger</th>
<th>Design</th>
<th>DRL</th>
<th>Crossing possible, I am yielding</th>
<th>Caution, I am not yielding</th>
<th>I see you</th>
<th>Automated mode</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Without explanation</strong></td>
<td><strong>14%</strong></td>
<td><strong>14%</strong></td>
<td><strong>0%</strong></td>
<td><strong>7%</strong></td>
<td><strong>18%</strong></td>
<td><strong>7%</strong></td>
<td><strong>7%</strong></td>
<td><strong>18%</strong></td>
</tr>
<tr>
<td><strong>After explanation</strong></td>
<td><strong>21%</strong></td>
<td><strong>4%</strong></td>
<td><strong>0%</strong></td>
<td><strong>29%</strong></td>
<td><strong>18%</strong></td>
<td><strong>7%</strong></td>
<td><strong>4%</strong></td>
<td><strong>4%</strong></td>
</tr>
</tbody>
</table>

Increasing from left to right.
Experiment 5: Animation 4 – crossing possible

Without explanation

<table>
<thead>
<tr>
<th></th>
<th>No danger</th>
<th>Design</th>
<th>DRL</th>
<th>Crossing possible, I am yielding</th>
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<th>I see you</th>
<th>Automated mode</th>
<th>Other</th>
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</tbody>
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Weighted sum → Intuitiveness = 4.1
**Experiment 5: Animation 5 – not yielding**

![Image](image.png)

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**Weighted sum → Intuitiveness = 2.8**

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Experiment 5: Animation 6 – crossing possible

Weighted sum → Intuitiveness = 2.9

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</tbody>
</table>

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Experiment 5: Animation 7 – yielding

![Image of a car with green lights]

- Caution, I am not yielding
- I see you
- Automated mode
- Other

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</tr>
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Weighted sum → Intuitiveness = 3.5

Graph showing relative frequency:
- Not intuitive: 29%, 18%, 4%, 0%, 4%
- Intuitive: 32%, 7%, 0%, 4%, 14%

The graph indicates a decrease in the percentage of participants selecting not intuitive options, and an increase in intuitive options.
Experiment 5: Animation 8 – yielding
Proposal from SAE

Slow flashing 1.67 Hz

Weighted sum → Intuitiveness = 2.8

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Experiment 5: Animation 9 – not yielding
Proposal from SAE

fast flashing 3.34 Hz

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</table>

Weighted sum → Intuitiveness = 2.8
Requirements

Color (according to CIE) ✓
- no need to continue studying amber and green as these are already used for other traffic safety purposes
- magenta is an understandable choice but also not supported by CIE
- turquoise seems to be the preferred solution / way to go: the definition of the borders of a X/Y color field would be a major outcome of Module 2B

Intensity ✓
- confirmation of a luminance value suitable for better vision would be a major outcome of Module 2B
- test set-up will ideally allow to confirm
- luminance value of xxxx cd/m² (> 5900) above which the visual recognition is better, or reaches a certain threshold
- different recognition thresholds for daytime and nighttime e.g. values comparable to DRL

Position ✓
- testing to be performed in such a way that both top mounting & frontend mounting are covered
- testing to confirm other possible influencing visual factors

Communication ✓
- the cyclist testing showed that subjects mix the interpretation of the turn indicator signal and the AD signal: a second round of tests with improved setup is needed to better distinguish which reaction of the test person relates to which signal
- setup to be split in a way to “leave” the communication topics to others and concentrate on the technical lighting part
- advice on the communication options related to existing studies is welcome (Module 1 literature studies, AVIP etc.)
Summary

CIE xy range for blue green

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
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<tbody>
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<td>0.34</td>
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Ambient luminance is the main factor on brightness perception

Luminance is a better indicator of brightness than luminous intensity

- Night: 5-17 kcd/m²
- Day: 14-33 kcd/m²

Small differences in the color naming in dark and light environment

No influence of the location on brightness perception in investigated situations

Explanation of animations improves comprehensibility
Open questions

Integration / Size
- Headlamp
- Side mirrors
- No fix position

Visibility (photometric values)
- Unobstructed field of vision
- Rush-hour traffic

Interrelation with
- DRL
- Low beam
- Other signals (direction indicator, warning light, etc)

Functions
- Indicating automated mode (on/off)
- Intention of ADS (animations, flashing, etc)
- Cooperation / interaction (additional comfort)
- Intercultural, simple, self-explanatory
Thank you for your attention!