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# EFFECT OF ILLUMINANCE ON PERCEPTION OF THE STROBOSCOPIC EFFECT

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## Abstract

A study deals with the stroboscopic effect that occurs during the perception of pulse width modulated light. The aim was to investigate whether and how illuminance influences the stroboscopic effect. The study was based on a test setup with a rotating black circle as a visual object on a bright background. The test field was illuminated with different illumination levels (1000 lx, 250 lx, 63 lx). The LED illumination varied in frequency, duty cycle and modulation depth. 12 test subjects took part. The hypothesis that the perception of the stroboscopic effect depends on the illuminance could not be confirmed.

*Keywords:* Stroboscopic Effect, Time-Modulated Light

## 1 Introduction

Light flicker is a periodically repeating change in the luminous flux of light sources. It occurs when the light sources are not operated with a constant current. This is referred to as pulsed operation, in which the light source is switched on and off at short intervals. Pulsed operation is also used for dimming light-emitting diodes. With pulse width modulation (PWM), the length of the light pulses becomes shorter the further they are dimmed.

Not every flicker of light is perceptible to the human eye. The more light pulses are presented per second, the higher the frequency of the luminous flux and the more difficult it is for the eye to distinguish between the light pulses. Above a certain frequency (flicker fusion frequency), they can no longer be seen separately; they merge into a constant perception of light.

For static situations in which neither the illuminated objects nor the observer's eye are moving, the flicker fusion frequency is below 90 Hz. In non-static situations where illuminated objects are moving, light flicker at frequencies greater than 90 Hz can also be seen as flicker. The so-called stroboscopic effect then occurs (Figure 1).



**Figure 1 – Left: motionless hand, centre: the moving hand still appears as a single object, right: the fingers of the hand can be seen multiple times due to the stroboscopic effect.**

The SVM value (Stroboscopic Visibility Measure) is used to assess the perception of the stroboscopic effect between 80 and 2000 Hz. A value of 1.0 means that an average observer recognizes the effect with a probability of 50%. In (EU, 2021) is required an  $SVM \leq 0.4$  for main voltage light sources under full load operation. However, the limit values mentioned do not apply

to dimmed operation of the luminaire. When dimming with pulse width modulation (PWM), however, the flickering can increase. This is not considered in the evaluation; no limit values are specified that must be maintained.

When dimming with pulse width modulation, the duty cycle changes. This is the proportion of time during which the light source is switched on (see Figure 4) and the illuminance decreases. The literature describes that the strength of the perceived stroboscopic effect depends on the ambient brightness (luminance or illuminance) (Frederiksen, 1980), (Perz, 2018). In the study presented here, the effects of PWM dimming and thus a variation in illuminance on the perception of the stroboscopic effect were investigated.

## 2 Test Setup

### 2.1 Test Stand

Studies on the stroboscopic effect (Vogels, 2011), (Perz, 2015) and (Perz, 2018) serve as a basis. The test setup used there was adapted. A circular visual object (diameter 2.7 cm) is placed on a rotating disk (radius 14 cm). The distance of the object from the center of the circle is 10.5 cm. The disk is embedded in a table top, in front of which the test person sits (see Figure 2 for dimensions). In contrast to the tests in (Vogels, 2011), (Perz, 2015) and (Perz, 2018), the turntable has a white surface and the visual object is black (reflectance: 0.03; contrast to white: 0.97). The viewing area and the surfaces of the enclosure are white (reflectance: 0.9).

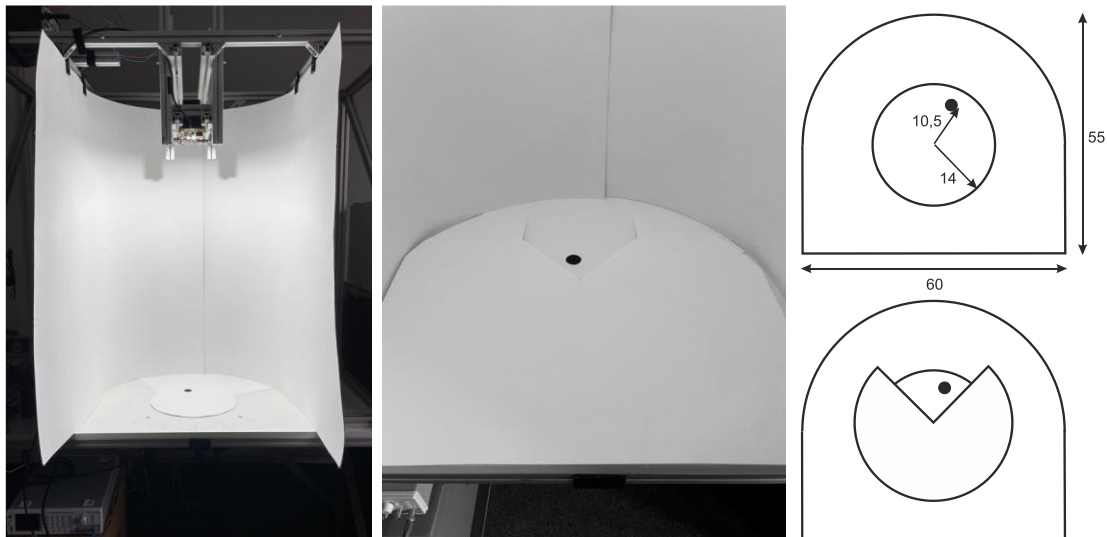


Figure 2 – Left: Photo of the test stand without cover, centre: Table surface with rotating disk an cover, top right: Sketch of the table surface without cover, bottom right: with cover

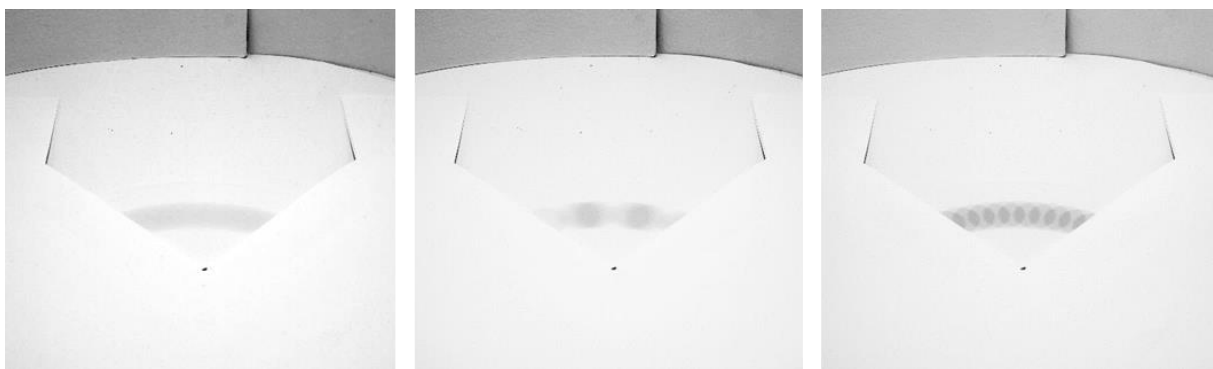


Figure 3 – Illustration of the perceived effects: left: no stroboscopic effect, centre and right: different stroboscopic effects due to illumination with different frequencies

Directly above the rotating disk, at a distance of 85 cm, there is a light-emitting diode as a light source. The tabletop, the area on which the test subject adapts, has an average luminance of 285 cd/m<sup>2</sup> (minimum 265 cd/m<sup>2</sup>, maximum 315 cd/m<sup>2</sup>) at 1000 lx illuminance.

The white LED has a color temperature of 4000 K and is controlled by the control unit of the Labarazzi system from VISO SYSTEMS. Luminous flux, frequency, duty cycle and modulation depth can be set independently of each other via a control PC with the Light Inspector 7 software from VISO SYSTEMS. The test was carried out exclusively with pulse-width modulated light (square-wave signal). The set values for frequency, duty cycle DC and modulation depth were checked using a Tektronix TDS 3014B oscilloscope with a photodiode sensor. The illuminance was set with an LMT pocket-lux luxmeter at a previously determined reference point on the table surface. All parameters were set and saved for an illuminance of 1000 lx on the table surface. The illuminance was varied to 250 lx and 63 lx by using filter foils with transmission levels of 25% and 6.25%.

Analogous to the studies (Vogels, 2011), (Perz, 2015) and (Perz, 2018), the disk rotates at a speed of 6.3 rotations per second. The visual object thus has a speed of 4 m/s, which corresponds to typical human movements (e.g. rapid movement of the hand).

Preliminary tests showed that the eye movements of the test subjects occasionally led to the perception of stroboscope-like phenomena even when illuminated with constant light. For this reason, 3/4 of the rotating disk was covered (Figure 2, right-hand side). Reducing the size of the section reduces the effects mentioned.

## 2.2 Parameter

The investigation was carried out exclusively with pulse-width modulated light. The light source can be controlled in defined time sequences. The frequency (f), the duty cycle (DC), the modulation depth (m) and the illuminance (E) were varied according to Table 1. The parameters could be set independently of each other. The parameters f, DC and m are defined in Figure 4. The combinations of frequency, duty cycle and illuminance result in 54 situations. In each of the situations, the modulation depth was varied in 7 steps during a test run, whereby the illuminance was kept constant by adjusting the luminous flux. In this way, the influence of the parameters could be investigated independently of each other.

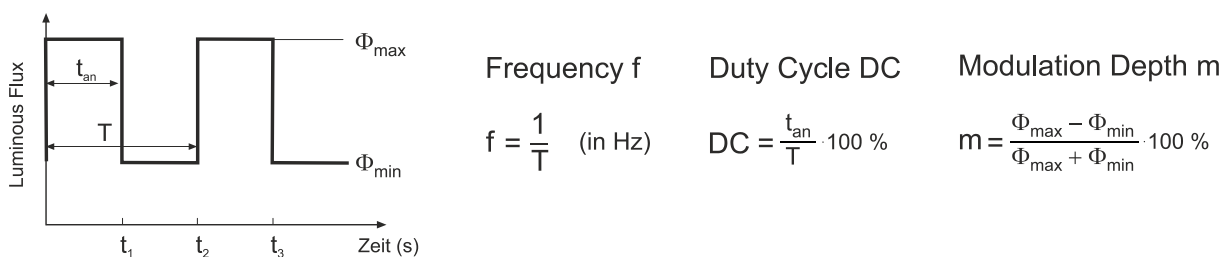


Figure 4 – Definition of the parameter

Table 1 – Examination parameter

Frequency f in Hz	100, 200, 400, 800, 1400, 2000
Duty Cycle DC in %	20, 50, 80
Modulation Depth m in %	100, 80, 63, 50, 40, 33, 0
Illuminance E in lx	1000, 250, 63

## 2.3 Testing Procedure

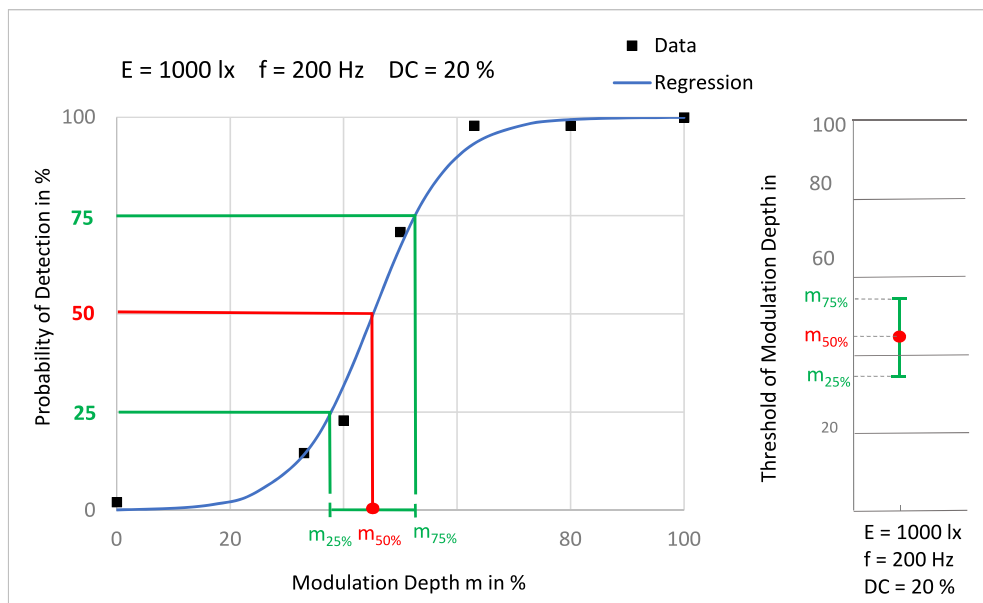
The 12 test subjects (6f, 6m, aged between 22 and 63) were shown the situation with a modulation depth of 100% and asked whether they perceived a stroboscopic effect. The modulation depth was then reduced to 80 % and queried again. In this way, the threshold of detection was determined with decreasing modulation depth. The same procedure was then repeated with increasing modulation depth.

Before starting, the procedure was explained to the test subjects and demonstrated using examples, for illustration see figure 3. The test run (ascending and then descending modulation depth) took place twice with each test subject. In this way, a total of 48 responses (4 per person) are available for each modulation depth. The situation with  $f = 400$  Hz and  $DC = 50\%$  occurred four times in each run, so that 192 responses are available for each modulation depth. One procedure with all repetitions lasted about 30 minutes per illuminance studied. Only one illuminance was examined per test day.

## 3 Evaluation

### 3.1 Determination of visibility threshold of modulation depths

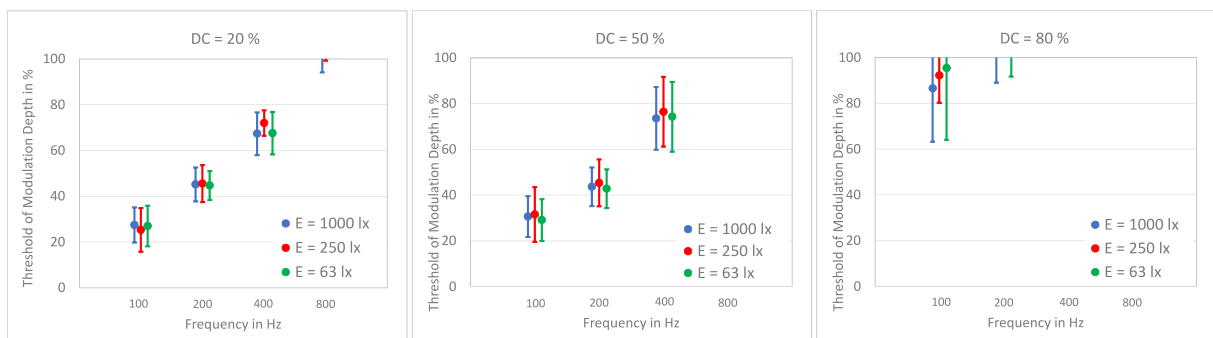
The subject's response is either "stroboscopic effect detected" or "stroboscopic effect not detected". The percentage of the response "stroboscopic effect detected" can be interpreted as the probability of detection and is shown in Figure 5 for one situation as a function of the modulation depth. A logistic regression was carried out with the data using the statistics program SPSS 27, with which the associated modulation depth can be determined for each detection probability. The average threshold is usually set at 50% detection probability (threshold modulation depth  $m_{50\%}$ ). The range between the modulation depths at which the detection probabilities are 25 % and 75 % is the quartile range (green area in Figure 5). In the following tables and illustrations, this is given as a measure of statistical dispersion of the thresholds (50% of the thresholds are within the quartile range). The lower quartile limit  $m_{25\%}$  is the modulation depth at which the stroboscopic effect is detected in 25% of cases, while the upper quartile limit  $m_{75\%}$  is the modulation depth at which the stroboscopic effect is detected in 75% of cases. The greater the modulation depth, the higher the probability of detection. Table 3 summarizes the threshold modulation depths with the quartile limits for all situations investigated.



**Figure 5 – Left: Detection probability for an exemplary situation as a function of the modulation depth: data from the study and the logistic regression function determined from it. The threshold value of the modulation depth ( $m_{50\%}$ ) and the modulation depths for the detection probabilities of 25% and 75% were determined from the regression function. Right: Illustration of threshold (red) and quartile distance (green)**

**Table 2 – Thresholds of modulation depths  $m_{50\%}$  with lower and upper quartile limits  $m_{25\%}$  and  $m_{75\%}$  (all values in %), missing values: the corresponding detection probability was not achieved**

	E in lx	1000	250	63	1000	250	63	1000	250	63
f in Hz	DC in %	Lower Quartile Limit (25 %)			Threshold (50 %)			Upper Quartile Limit (75 %)		
100	20	20	16	18	27	25	27	35	35	36
	50	22	20	20	31	32	29	40	43	38
	80	63	75	64	87	92	95			
200	20	38	37	38	45	46	45	53	54	51
	50	35	35	34	44	45	43	52	56	51
	80	89	94	92						
400	20	58	66	58	67	72	68	77	78	77
	50	60	61	59	74	76	74	87	92	89
	80									
800	20	94	99							
	50									
	80									



**Figure 6 – Diagrams of the results from Table 2: Threshold of modulation depth with quartile spacing, plotted as a function of frequency for different illuminance levels and duty cycles**

As expected, the frequency has a very large effect. This shows an increase in the threshold value with increasing frequency (Figure 6). Above a frequency of 800 Hz, the stroboscopic effect is only detected with a low probability, even at maximum modulation depth  $m = 100\%$ . The lower quartile limit  $m_{25\%}$  is only reached in two situations (DC = 20 % at E = 1000 lx and E = 250 lx). In all other cases, the detection probability is below 25 %.

Three duty cycles were examined. As can be seen in Figure 6, there are only slight differences between DC = 20 % and DC = 50 %. At a duty cycle of 80 %, however, even high modulation depths are only detected with low probabilities. At frequencies of 400 Hz and more, the detection probabilities are below 25 %.

As duty cycles of 60 % and 70 % were not investigated, no statement can be made about this. Light sources that are operated with DC = 80 % are only slightly dimmed. In most cases, higher dimming levels are required. A clear statement on the effect of the duty cycle in the range between 50 % and 80 % would be important in practice and will be investigated in a follow-up project.

The hypothesis that the perception of the stroboscopic effect depends on the illuminance could not be confirmed by the study. The results for illuminance levels from 63 lx to 1000 lx are essentially the same (Figure 6).

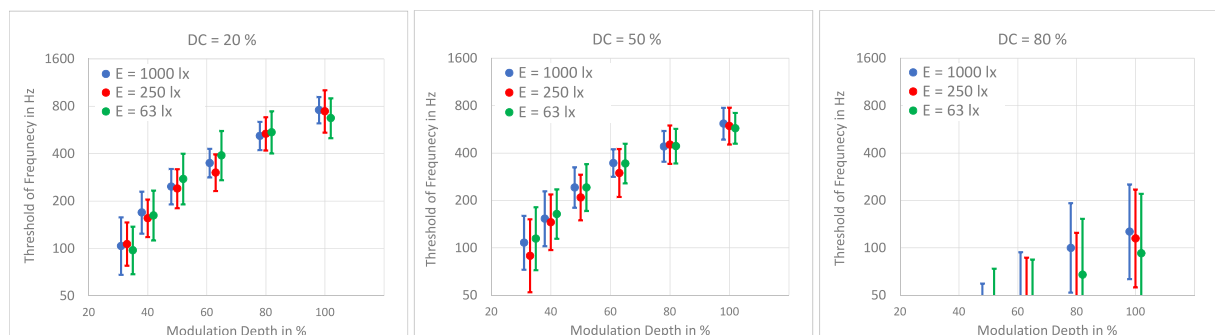
### 3.2 Determination of visibility threshold of the frequency

To determine threshold frequencies, a logistic regression of the determined detection probabilities was now carried out as a function of the frequency, analogous to the evaluation in Chapter 3.1 (Figure 5).

The threshold frequency  $f_{50\%}$  is the frequency at which the average probability of detection is 50%. The probability of detection decreases with increasing frequency. Therefore, the upper quartile limit  $f_{25\%}$  is the frequency at which the stroboscopic effect is detected 25% of the time, while the lower quartile limit  $m_{75\%}$  is the frequency at which the stroboscopic effect is detected 75% of the time. Table 4 summarizes the threshold frequencies with the quartile limits for all situations investigated.

**Table 3 – Visibility thresholds of frequency  $f_{50\%}$  with lower and upper quartile limits  $f_{75\%}$  and  $f_{25\%}$  (all values in Hz), missing values: the corresponding detection probability was not achieved**

	E in lx	1000	250	63	1000	250	63	1000	250	63
m in %	DC in %	Lower Quartile Limit (25 %)			Threshold (50 %)			Upper Quartile Limit (75 %)		
100	20	623	544	502	755	742	672	915	1011	899
	50	487	453	458	614	594	574	775	777	719
	80	63	56	39	127	115	92	253	234	221
80	20	422	418	401	518	534	546	637	682	743
	50	352	341	344	440	452	442	552	599	569
	80	52	13	30	100	41	67	192	125	153
63	20	282	232	271	348	303	389	429	396	557
	50	282	211	257	346	299	343	423	424	458
	80	26	13	16	49	33	37	94	87	84
50	20	190	180	190	247	240	276	319	319	399
	50	180	150	171	242	209	242	325	291	341
	80	14		20	29		39	59		74
40	20	124	118	112	169	155	162	229	204	233
	50	102	97	114	153	145	164	229	218	236
	80									
33	20	68	78	69	103	106	97	157	146	138
	50	73	52	72	108	89	115	160	152	182
	80									



**Figure 7 – Diagrams of the results from Table 4: Thresholds of frequency with quartile spacing, plotted as a function of the modulation depth for different illuminance levels and duty cycles**

As expected, the threshold frequency depends strongly on the modulation depth (Figure 7). A comparison of the investigated duty cycles shows no difference between the duty cycles DC =

20 % and DC = 50 %. At a duty cycle of DC = 80 %, the threshold frequencies are lower than at the lower duty cycles.

If we consider the modulation depth of  $m = 100\%$  most commonly used in practice for PWM dimming, the stroboscopic effect can only be recognized with a probability of 50 % above a frequency of 115 Hz at a duty cycle of DC = 80 %, while the threshold at DC = 20 % is 742 Hz.

### 3.3 Generalized Estimating Equations

Using the statistical model “Generalized Estimating Equations”, a form of the “generalized linear model”, the effects on the binary response of the test subjects (1 = “stroboscopic effect detected”, 0 = “stroboscopic effect not detected”) were determined with the statistics program SPSS 27. The factors used were the direction of the tests (descending or ascending modulation depth) and the repetition of the sequence, and the covariates used were illuminance, the logarithm of the frequency, the duty cycle and the modulation depth. The test of the model effects showed no significant influence of direction, repetition and illuminance. As expected, frequency, duty cycle and modulation depth had a significant influence.

A comparison of the male and female test subjects showed no significant difference, while the comparison between younger test subjects (22-33 years) and older test subjects (56 to 63 years) showed a significant difference. The older test subjects are clearly less sensitive.

**Table 4 – Effects of the “Generalized Estimating Equations” model on the dependent variable response of the test subject**

	Significance of Wald-Chi-Square
(Constant Term)	0,000
E	0,660
Direction of Test	0,739
Repetition of the sequence	0,925
log (f)	0,000
DC	0,000
m	0,000

## 4 Comparisons with the literature

All studies with which our results are to be compared were carried out with test setups from (Vogels, 2011), (Perz, 2015) and (Perz, 2018). In contrast to our setup, the visual object was a white circle on a black background. In our study, the visual object was black and the surroundings were white. The far environment (wall behind the test setup) was white in both studies. Due to these differences, the adaptation conditions are different for the same specified illuminance. The bright environment in our study resulted in higher adaptation luminance. In order to be able to compare the results nevertheless, our results for the lowest illuminance  $E = 63\text{ lx}$  are used in the following tables. Nevertheless, the results are not directly comparable, as the luminance levels in the comparative studies may have been much lower than in our study.

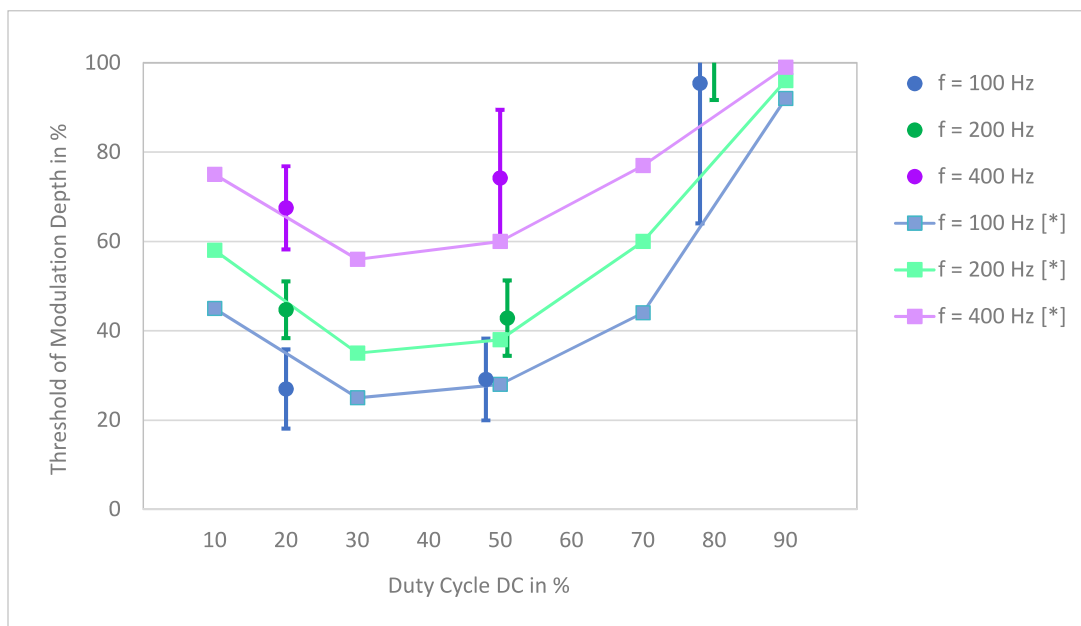
(Vogels, 2011) investigated the threshold modulation depth for different frequencies and duty cycles. The illuminance was 500 lx. The results are compared with the results of our study in Table 5. Here too, the perception threshold increases with frequency.

The effect of the duty cycle is different. In (Vogels, 2011), the threshold modulation depth initially decreases (when increasing from DC = 10 % to DC = 30 %) and then increases again (Figure 8). In our study, there is no difference between DC = 20 % and 50 %, after which the threshold modulation depth increases more significantly. Our threshold values are larger than in (Vogels, 2011). For example, the results for DC = 80 % correspond to those for DC = 90 %.

Comparisons with results from (Perz, 2015) (Table 6) also show higher threshold modulation depths in our study.

**Table 5 – Results at 63 lx compared with the data from in (Vogels, 2011) at 500 lx**

	TU Ilmenau (63 lx)			(Vogels, 2011) (500 lx)				
DC =	20 %	50 %	80 %	10 %	30 %	50 %	70 %	90 %
f = 50 Hz				40 %	27 %	28 %	32 %	75 %
f = 100 Hz	27 %	29 %	95 %	45 %	25 %	28 %	42 %	92 %
f = 200 Hz	45 %	43 %		57 %	34 %	37 %	59 %	97 %
f = 400 Hz	68 %	74 %		76 %	55 %	59 %	76 %	99 %



**Figure 8 – Threshold modulation depth with quartile distance at E = 63 lx. For comparison, the thresholds from (Vogels, 2011) are inserted as solid lines [\*]**

**Table 6 – Threshold modulation depths at 63 lx in comparison with (Perz, 2015) at 500 lx**

	TU Ilmenau (63 lx)	(Perz, 2015) Exp. 2 (500 lx)	(Perz, 2015) Exp. 2 (500 lx)
	DC = 50 %	DC = 50 %	Sinus
f = 50 Hz		15 %	25 %
f = 100 Hz	29 %	24 %	32 %
f = 200 Hz	43 %	33 %	40 %
f = 400 Hz	74 %	41 %	55 %

In (Perz, 2018), the dependence of the threshold modulation depth on the illuminance was explicitly investigated. However, a sinusoidal time course was used there. The same applies to (Wang, 2014).

In both comparative studies, the lowest threshold modulation depths were determined at an illuminance of 50 lx (Table 7). Lower and higher illuminance levels led to higher threshold values. Our results do not show this dependence. However, values below E = 63 lx were not investigated.

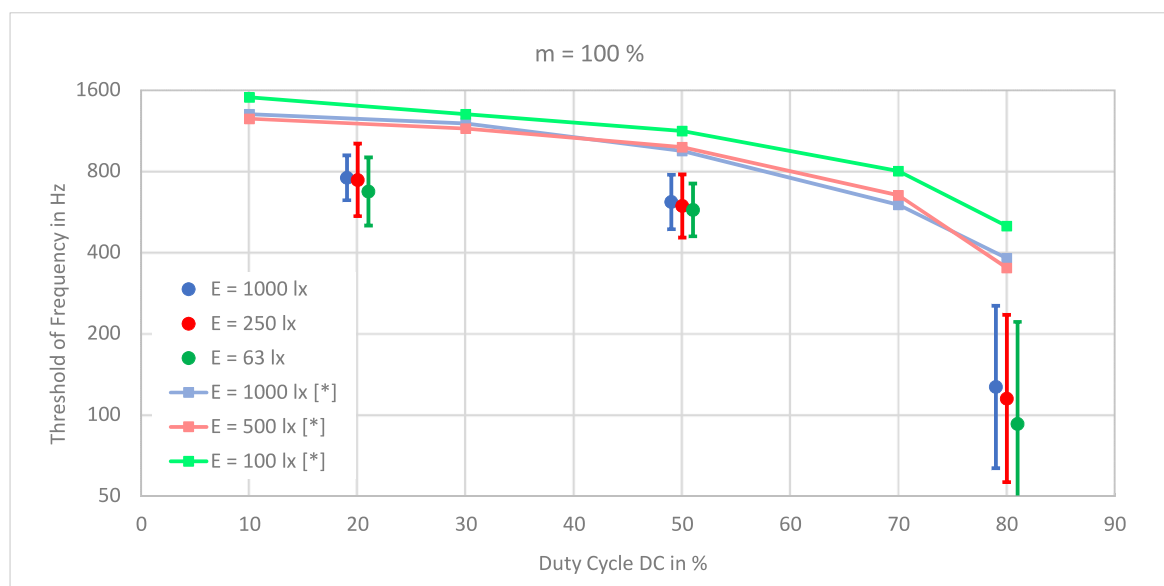
**Table 7 – Threshold modulation depths in comparison with (Perz, 2018) and (Wang, 2014)**

	TU Ilmenau	(Perz, 2018)	(Wang, 2014), quoted from (Perz, 2018)
	f = 100 Hz, DC = 50 %	f = 100 Hz, sinus	f = 100 Hz, sinusförmig
E = 5 lx		40 %	31 %
E = 10 lx		30 %	24 %
E = 63 lx / 50 lx	29 %	18 %	19 %
E = 100 lx		23 %	
E = 250 lx	32 %		
E = 500 lx		27 %	26 %
E = 1000 lx	31 %		

In a study by (Chen, 2023), PWM-modulated light with a modulation depth of 100 % was used to investigate the perception of the stroboscopic effect. An experimental setup according to (Vogels, 2011), (Perz, 2015) and (Perz, 2018) was also used here. As in our study, there was a dependence on the duty cycle but no dependence on the illuminance (Table 8 and Figure 9). However, the threshold frequencies are higher overall than in our studies.

**Table 8 – Threshold frequencies (in Hz) compared with (Chen, 2023)**

DC =	TU Ilmenau			(Chen, 2023)				
	20 %	50 %	80 %	10 %	30 %	50 %	70 %	90 %
E = 1000 lx	755	614	127	1300	1200	950	600	380
E = 500 lx				1250	1150	980	650	350
E = 250 lx	742	594	115					
E = 100 lx				1500	1300	1125	800	500
E = 63 lx	672	574	92					



**Figure 9 – Comparison of the results with the data from (Chen, 2023) as solid lines [\*]**

## 5 Summary

The study investigates the stroboscopic effect that occurs during the perception of flickering light, especially when light sources are operated with pulse width modulation (PWM). The investigation was based on a test set-up with a rotating a visual object. The object moved at a speed of 4 m/s. The test field was illuminated with different illuminance levels (1000 lx, 250 lx, 63 lx). The LED illumination varied in frequency, duty cycle and modulation depth. 12 test subjects took part in the study.

The main aim of the study was to investigate whether and how illuminance influences the stroboscopic effect with PWM dimming, as this effect has not been considered in the SVM assessment to date. The assumption that the perception of the stroboscopic effect depends on the illuminance could not be confirmed by the study. The results for illuminance levels from 63 lx to 1000 lx are essentially the same.

If we look at the dependency on the frequency, we see, as expected, an increase in the threshold value with increasing frequency. An increase in the duty cycle also leads to an increase in the threshold value, whereby the results of DC = 20 % and DC = 50 % do not differ. At a duty cycle of DC = 80 %, the threshold frequencies are lower than at the lower duty cycles.

In order to derive practical conclusions from the results, the most critical case (modulation depth  $m = 100\%$  and duty cycle DC = 20 %) should be used. In this case, frequencies of  $f = 1000$  Hz and more are detected with a probability of less than 25 % (upper quartile limit, Figure 7 left).

A perception of stroboscopic effects by the test subjects in situations with an SVM  $\leq 0.4$  was not detectable with the test data. The probability of the test subjects perceiving stroboscopic effects in situations with a frequency  $f > 800$  Hz is less than 50 %, regardless of the SVM value. At a frequency  $f > 1000$  Hz, the probability of detection is less than 25 % regardless of the SVM value.

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