

Review

A Review of Stroboscopic and Phantom Array Effects in Light-Emitting Diode Lighting

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Abstract

The stroboscopic effect and phantom array effect caused by temporal light modulation (TLM) in light-emitting diode (LED) lighting are important temporal light artifacts (TLAs) that can influence visual perception, task performance, and visual comfort. This review systematically analyzes 40 studies published between 1998 and 2024 to provide a comprehensive overview of the current understanding of both effects. The reviewed literature covers visibility thresholds, influencing parameters, experimental methodologies, and assessment metrics. The analysis shows that reported visibility thresholds for the stroboscopic effect typically range from 550 to 1000 Hz, whereas thresholds for the phantom array effect may extend to 10–15 kHz, suggesting substantial differences in the underlying perceptual mechanisms. In addition to modulation frequency, modulation depth, waveform, duty cycle, luminance, retinal image motion, and observer factors have been identified as important determinants of visibility. The review further highlights significant methodological differences among studies, including variations in experimental design, stimulus generation, participant characteristics, and psychophysical procedures. Although the stroboscopic visibility measure (SVM) provides a standardized framework for evaluating the stroboscopic effect, no comparably validated metric is currently available for the phantom array effect. The review identifies major knowledge gaps regarding the interaction of influencing parameters and the lack of standardized assessment methods. Future research should focus on establishing unified experimental protocols and developing robust metrics for the phantom array effect to support comprehensive lighting standards that protect visual comfort, well-being, and consumer health.

Keywords: temporal light artifacts; stroboscopic effect; phantom array effect; light-emitting diodes; visual perception



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1. Introduction

Pulse-width modulation (PWM) is a widely used method for controlling and dimming light-emitting diodes (LED), but it can introduce temporal light artifacts (TLAs) such as flicker, the stroboscopic effect and the phantom array effect [1,2]. Flicker refers to perceivable temporal variations in light intensity, whereas the stroboscopic and phantom array effects manifest as spatial distortions of visual perception. In these cases, moving objects may appear to follow segmented rather than continuous trajectories, or stationary light sources may be perceived as multiple discrete images during rapid eye movements

(saccades) [3]. While flicker has been extensively studied, the stroboscopic and phantom array effects remain insufficiently understood and require further investigation [4,5]. The increasing relevance of these phenomena is closely linked to the growing prevalence of LED technology [6]. Due to their high energy efficiency, longevity and precise controllability, LEDs have become the dominant light source across residential, industrial, automotive and public lighting applications [7,8]. For this review, the critical terms are explained and defined in Table 1.

This growth is driven by declining costs, improved energy efficiency and advancements in smart-lighting technologies [9–11]. A 2019 study by the Fraunhofer Institute, for example, demonstrated that German companies switching to LED lighting could achieve annual energy savings of 52 GWh by dynamically adjusting illumination according to external conditions such as the time of day [12]. In automotive lighting, LEDs are increasingly preferred due to their capability to produce monochromatic light without filters and rapidly modulate light signals [13]. Furthermore, LEDs are widely used in public street lighting, stage lighting, greenhouse illumination and emergency lighting, where dimming capabilities are crucial [14].

Table 1. Terms and definitions for temporal light modulation.

Preferred Term	Definition of Term	Alternate Term
Temporal Light Modulation (TLM)	Fluctuation in luminous quantity or spectral distribution of light with respect to time.	None
Direct Flicker Effect	Perception of visual unsteadiness induced by a light stimulus, the luminance or spectral distribution of which fluctuates with time, for a static observer in a static environment.	Flicker
Stroboscopic Effect (SE)	Change in motion perception induced by a light stimulus whose luminance or spectral distribution fluctuates with time, for a static observer in a non-static environment.	Stroboscopic Motion
Phantom Array Effect (PAE)	Change in perceived shape or spatial positions of objects induced by a light stimulus whose luminance or spectral distribution fluctuates with time, for a non-static observer in a static environment.	Ghosting

However, most LEDs are not powered directly from the electrical mains (i.e., the utility grid); instead, they include a driver circuit that converts the input Alternating Current (AC) power to a regulated Direct Current (DC) voltage, controlling the current flowing through the LED [15]. Figure 1 illustrates representative luminous output waveforms for various driver configurations. In addition, the LED current can be modulated through dimming or intensity control. The most common dimming method is PWM, in which temporally variable signals can induce temporal light artifacts, including flicker, the stroboscopic effect and the phantom array effect [3]. An example of PWM dimming is shown in Figure 2. While flicker phenomena related to PWM have been extensively studied, the stroboscopic effect and especially the phantom array effect remain less understood [4,16,17]. The parameters influencing these effects are not yet fully characterized and inconsistent findings complicate the establishment of clear guidelines [18].

Existing studies have reported a wide range of visibility thresholds for both the stroboscopic and phantom array effects, reflecting substantial differences in experimental methodologies, stimulus characteristics, observer populations, and psychophysical assessment procedures. Although several technical parameters, including modulation frequency, modulation depth, waveform, duty cycle, and retinal image motion, have been identified as influential factors, their relative contributions remain unclear and, in some cases, contradictory findings have been reported. Furthermore, while the stroboscopic visibility measure (SVM) provides a standardized framework for evaluating the stroboscopic effect, no universally accepted metric currently exists for the phantom array effect. Consequently, the lack of methodological

consistency and standardized assessment approaches limits the comparability of existing studies and hinders the development of comprehensive lighting standards.

Several approaches have been proposed to reduce the visibility of stroboscopic and phantom array effects. These include increasing modulation frequency, implementing hybrid dimming techniques, and employing optical diffusers to smooth temporal fluctuations [19–21]. However, most mitigation strategies have been evaluated under controlled laboratory conditions, and evidence regarding their effectiveness in realistic lighting applications remains limited. As a result, the practical implications of these approaches for visual comfort, task performance, and long-term user acceptance are still not fully understood.

To address these challenges, this review provides a comprehensive synthesis of current research on the stroboscopic and phantom array effects. Particular emphasis is placed on comparing reported visibility thresholds, identifying the influence of technical and geometric parameters, evaluating methodological differences among studies, and assessing existing evaluation metrics. By highlighting unresolved questions and methodological limitations, this review aims to support the development of standardized assessment procedures and guide future research toward more robust and comprehensive lighting standards.

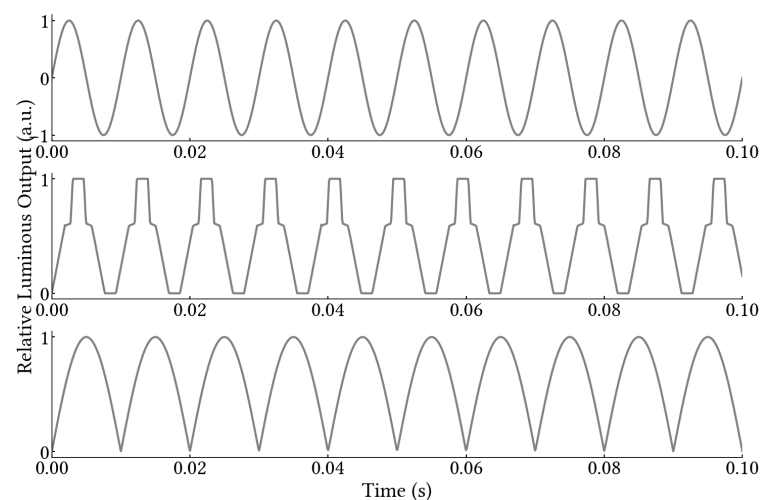


Figure 1. Relative luminous output from an light-emitting diodes (LED) when different drivers are used.

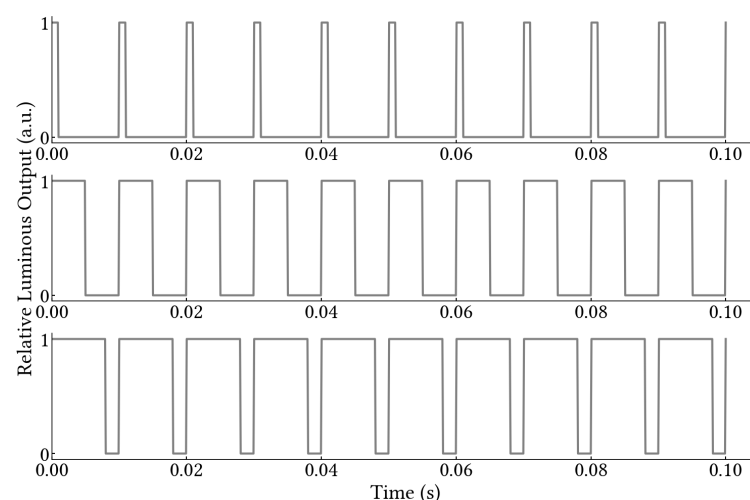


Figure 2. Relative luminous output from an LED under pulse-width modulation (PWM) dimming at 10%, 50%, 80% duty cycles, where the duty cycle is defined as the fraction of one period during which the signal is ON.

The remainder of this paper is structured as follows: the methodological approach is detailed in Section 2, research results on the two effects are summarized in Section 3, identified research gaps and open questions are discussed in Section 4 and conclusions are drawn in Section 5.

2. Methods

We conducted a structured literature review to establish the current state of research on temporal light artifacts, identify open research questions and propose directions for future work. The review followed the methodological framework described by Webster and Watson (2002) [22]. Rather than providing an extensive discussion of theoretical foundations, the review focused on clearly defining the key concepts necessary for understanding the stroboscopic and phantom array effects.

Relevant publications were identified through the following datasets: Google Scholar, EBSCOhost, and Web of Science. The literature search covered publications from January 1998 to December 2024. The following keywords were used: “Stroboscopic Effect”, “Phantom Array Effect”, and “Temporal Light Artifacts”. Search queries were constructed using combinations of the keywords in conjunction with the logical operator “AND” and the terms “LED,” “Light,” or “Luminaire.” The search was restricted to studies explicitly investigating LED light sources, while publications addressing other forms of illumination were excluded.

An initial screening was performed based on titles, keywords and abstracts. Priority was given to laboratory studies and general investigations of the stroboscopic and phantom array effects. Conference papers, commentaries, presentations and studies primarily focused on flicker were excluded. No additional temporal or disciplinary restrictions were applied to ensure comprehensive coverage of the relevant literature.

To minimize the risk of including older or less relevant publications, all articles identified through citation tracking were screened for relevance to temporal light artifacts. Older studies were only included when they provided foundational insights or widely cited methodologies critical to understanding the stroboscopic or phantom array effects.

3. Results

The majority of the published work addresses the stroboscopic effect, with 22 relevant studies analyzed, compared to 18 studies on the phantom array effect. Figure 3 presents the flow diagram of literature selection, illustrating the screening and inclusion process for the 40 studies analyzed in this review. One publication investigates a combined phenomenon, referred to as the “stroboscopic phantom array effect” [23] and is therefore discussed in the context of the phantom array effect.

The reviewed studies span the period from 1998 to 2024, with approximately 60% of the publications appearing since 2019. A complete overview of all included studies is provided in Tables 2 and 3.

To facilitate comparison across studies, Figure 4 illustrates the annual distribution of publications between stroboscopic effect and phantom array effect research. The bar height represents the total number of studies published per year, while the annotations above each bar summarize the modulation frequency ranges investigated in that year. Years marked with “X” indicate that no specific frequency range was explicitly reported. This graphical summary complements the detailed parameter listings in Tables 2 and 3 and enables a clearer assessment of temporal research trends.

The following sections summarize the reported empirical findings for both effects, organized by investigated parameters and experimental configurations, to provide a descriptive comparison across studies.

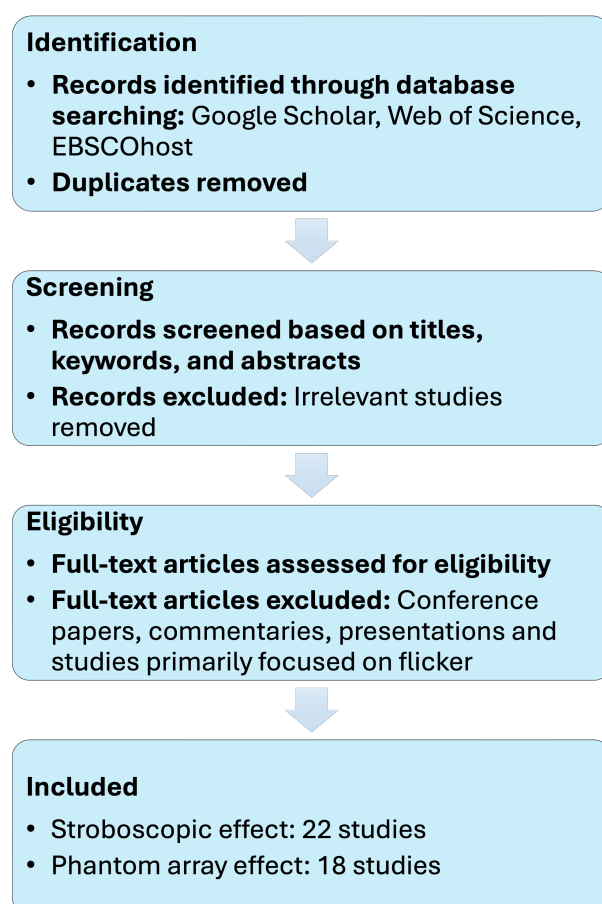


Figure 3. The flow diagram of literature selection, illustrating the screening and inclusion process for the 40 studies analyzed in this review.

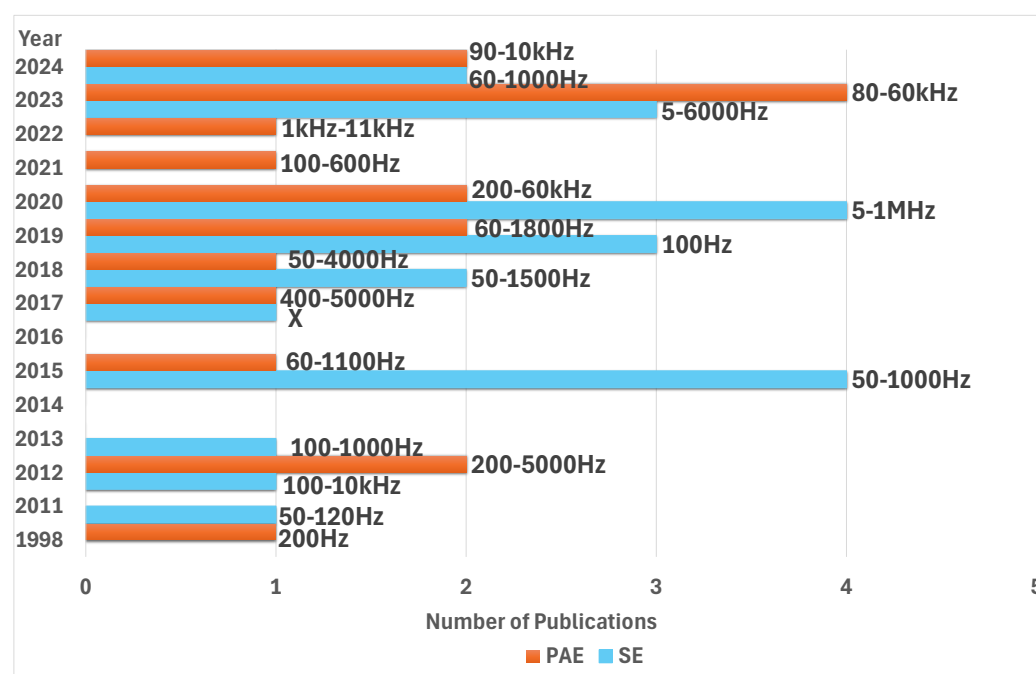


Figure 4. Annual distribution of the reviewed studies (1998–2024). The height of the bars represents the total number of publications per year. Different colors distinguish studies on the stroboscopic effect (SE) and the phantom array effect (PAE). The values above each bar indicate the modulation frequency ranges investigated in the respective year; “X” denotes that no explicit frequency range was reported.

Table 2. Literature overview—stroboscopic effect (SE).

Reference	Frequency	SVM	Modulation Depth (Percent Flicker)	Duty Cycle	Waveform	Color Temperature (CCT)	Speed	Illuminance	Age and Gender	Others
Bullough et al. (2011) [24]	50–120 Hz	X	33%, 100%	10%, 50%, 60%, 100%	Sinus (chopped), Rectangle	2700, 4000, 6000 K	variable	400 lx on surface	10 participants (3F, 7M), 23–55 years (34 avg)	Flicker Index: 0.17, 0.41, 0.5, 0.9
Bullough et al. (2012) [25]	100, 300, 1000, 3000, or 10,000 Hz	X	Percent Flicker (100, 54, 25, 5%)	50%	Sinus, Rectangle	4000 K	variable	400 lx on surface	10 participants (4F, 6M), 23–52 years (31 avg)	Flicker Index: 0.5, 0.27, 0.13, 0.03
Tu et al. (2013) [26]	100, 150, 200, 250, 300, 400, 500, 750, 1000 Hz	X	0–100%	X	X	6200 K	4 m/s	500 lx (horizontal disk)	21 participants (10F, 11M), 21–47 years (25 avg)	
Perz et al. (2015) [27]	50, 100, 200, 400, 800 Hz	X	Exp. 1: modulation depth staircase	50%	Sinus, Rectangle	4800 K	4 m/s, 8 m/s	500 lx	Exp1: 22 participants (12F, 10M), 19–33 years; Exp2: 50 participants (33F, 17M), 19–48 years; Exp3: 20 participants (12F, 8M), 19–36 years;	4 cases: with and without reference light, with or without cover (What influence does the length of the curve / trajectory have?)
Wang et al. (2015) [28]	Exp1: 50, 100, 200, 400 Hz; Exp2: China–100, 150, 200, 250, 300, 400, 500, 750, 1000 Hz; Europe–100, 200, 400, 800 Hz; Exp3: 50, 100, 200, 400 Hz	X	0–100%	10%, 30%, 50%, 70%, 90%	Sinus, Rectangle	X	2, 4, 8 m/s	500 lx horizontal illuminance on disk; Exp 4: 5 lx, 10 lx, 30 lx, 50 lx, 100 lx, 300 lx, 500 lx	X	
Polin et al. (2015) [29]	100, 200, 300, 400, 1000 Hz	X	20%, 40%, 100%	20%, 50%, 100%	X	4000 K	2–5 m/s (variable)	250 lx	38 participants (23F, 15M), 22–62 years (33 avg)	Luminance of the tabletop surface: 60 cd/m ² , grouping by: age, gender, condition
Bullough et al. (2016) [30]	100, 120, 300, 1000 Hz	X	Percent Flicker (100% or 27–65%)	60%, 75%, 90%	Rectangle /Trapezoidal /Triangular	X	Metro-nome: 1, 7 m/s and variable	Horizontal illuminance: 300 lx on the table	10 participants; Exp. 1: 23–43 years (32 avg); Exp. 2: 23–51 years (35 avg)	Flicker Index also taken into account

Table 2. Cont.

Reference	Frequency	SVM	Modulation Depth (Percent Flicker)	Duty Cycle	Waveform	Color Temperature (CCT)	Speed	Illuminance	Age and Gender	Others
Polin et al. (2017) [31]	X	X	1%, 5%, 10%, 20%	X	X	X	X	X	13 participants; 21–37 years	
Perz et al. (2018) [32]	Exp. 1 and 2: 50, 100, 200, 400 Hz; also 800 Hz in Exp. 3; Exp 4: 100, 150, 200, 250, 300, 400, 500, 750, 800 Hz	X	0–100%	5%	Sinus	6500 K	4 m/s	Exp. 1–4: 500 lx; Exp. 5: 200 lx (and 100 lx ?); Exp. 6: 5, 10, 50, 100, 500 lx	Exp. 1: 12 participants (7M, 5F) 18–38 years; Exp. 2: 20 participants (13M, 7F) 19–33 years; Exp. 3: 20 participants (12M, 8F) 19–36 years; Exp. 4: 21 participants (10F, 11M) 21–47 years; Exp. 5: 9 participants (3F, 6M) 27–52 years	12:1 contrast on the disk
Zhao et al. (2018) [33]	100, 400, 1500 Hz	X	10%, 30%, 70%	X	X	4000 K	X	300 lx	10 students (4M, 6F) 22 years	Ra > 85, UGR < 19
Perz et al. (2018) [34]	100 Hz	X	X	50%	Rectangle	4800 K	X	500 lx horizontal illuminance	Exp. 1: 22 participants (12M, 10F) 19–33 years	
Veitch et al. (2019) [35]	X	0, 0.4–0.6, 1, 1.6 and >2	X	X	Sinus	2700–3000 K	X	330–350 lx on table	36 participants (18 each from France and Canada)	Ra = 80–85
Zhao et al. (2019) [36]	X	0.06, 0.5, 1, 1.5, 2.5, 3	X	X	Sinus	4000 K	X	500 lx	10 participants (4M, 6F) 19–23 years	Ra > 85
Veitch et al. (2020) [37]	100, 120 Hz	0, 0.4, 0.9, 1.4, 3.0	approx 3–80%	X	Sinus	2700–3000 K	4 m/s	330–350 lx	85 participants (27 tested in France and 58 in Canada) < 32 years	800 lm output, Pst << 1, Ra: 80–85, Glare sensitivity of the participants
Sekulovski et al. (2020) [38]	100 Hz	SVM: Reference = 0.47% and Intervention Lamp = 1.34%	Reference: 12.5% and Intervention Lamp: 36.4%	X	Sinus	X	X	500 lx on surface	46 participants (4F, 42M) 36–65 years, approximately 30 valid questionnaires	Daylight through the window

Table 2. Cont.

Reference	Frequency	SVM	Modulation Depth (Percent Flicker)	Duty Cycle	Waveform	Color Temperature (CCT)	Speed	Illuminance	Age and Gender	Others
Ayprandi et al. (2020) [39]	5 Hz to >1 MHz	Based on frequency as the visibility threshold	X	between 0–100%	Sinus	3000 K	4 m/s	100 lx	30 participants (20M, 10F) 27–35 years	540 lm
Zhao et al. (2020) [40]	100, 400, 1500 Hz	0.4–0.7 approx	10%, 30%, 70%	X	Sinus	4000 K	4 m/s (variable)	300 lx	10 participants (4M, 6F) 23.5 ± 3.5 years	UGR < 19, Ra = 85
Miller et al. (2024) [41]	90–6000 Hz	X	0–100%	For rectangular waveforms: 10%, 30%, 50%	Sinus /Rectangle	2871 K	Exp. 2: Stroboscopic Effects: white wand with tangential velocity of 4 m/s	X	36 participants (15F, 20M and 1 non-binary) 19–76 years	luminance 38,700 cd/m ²
Tan et al. (2024) [42]	5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 120, 600, 1000, 2000, 6000 Hz	X	100%, 60%, 20%, 10%	For rectangular waves: 90%, 50%, 30%, 10%	Sinus /Rectangle	X	X	X	X	
Veitch et al. (2024) [43]	100, 500 Hz	X	100%	50%	Rectangular	4100 K	X	500 lx	34 pariticipants (27F, 7M) 18–26 years	
Kang et al. (2024) [44]	60, 100, 400, 1000 Hz	0, 4.77, 4.97, 2.06, 1.31	100%	50%	square	X	X	400 lx	32 participants (10F, 22M) 20–30 years	
Zhao et al. (2025) [45]	100, 200, 400, 600, 800, 1000 Hz	0.060, 0.500, 1.000, 1.500, 2.500, 3.868	91.88%, 86.35%, 87.26%, 78.68%, 45.48%, 5.92% (under different frequency)	X	Sinus	4000 K	4 m/s	500 lx	10 participants (6F, 4M) 20.80 years on average	

Note: Zhao et al. (2025) [45]: “The Impact of Temporal Light Modulation on Psychological Responses Assessed by the Stroboscopic Visibility Measure” was published online in 2024 and is therefore classified as a 2024 publication in this analysis.

Table 3. Literature overview—phantom array effect (PAE).

Reference	Frequency	Illumination	Chromaticity	Modulation Depth/Duty Cycle	Waveform	Angle	Number, Age and Gender	Experiment
Hershberger et al. (1998) [46]	200 Hz	175 mlx	Red	1 ms ON and 4 ms OFF	X	0.2°	75 participants	LED fixed in front of participants, gaze between room corners
Vogels et al. (2012) [47]	200, 400, 1000, 3000 Hz	64, 2000, 10,000 cd/m ²	White	Duty cycle 0.2, 0.5, 0.8	Rectangle	Angle width: 0.5°, 1°, 2°; Saccades: 40°	15 participants (10M, 5F), 22–45 years	Black screen with a line
Roberts et al. (2013) [48]	1000, 2000, 3000, 5000 Hz	<1 lx environment; line: 0.02 to 310 cd/m ²	Green	Modulation depth: 5, 10, 20, 40%	Rectangle /Sinus	20°, 40° saccades	Exp. 1: 11 participants (7F, 4M), 22 and 65 years, 34 years on average; Exp. 3: 3 participants, 25–38 years	Box with a vertical light line (Small, Medium, Large)
Polin et al. (2015) [29]	Exp. 5.2: >1100 Hz?; Exp. 5.3: 60, 200, 400, 800 Hz; Exp. 5.4: from 100, 200, 400 Hz	Exp. 5.2: 0.1 cd/m ² object luminance; Exp. 5.3: 3 cd/m ² –6400 cd/m ² ; Exp. 5.4: 10, 20, 40, 60, 80, and 100% of the maximum luminance	Exp. 5.2: 450 (blue), 520 (green), and 625 (red) nm; Exp. 5.3: White 5000 K; Exp. 5.4: White 5700 K	Exp. 5.2: between 15%; Exp. 5.3: 20, 50%; Exp. 5.4: 10, 20, 40, 60%	X	Exp. 5.2: Ring width 0.57°, horizontal and vertical Saccades; Exp. 5.3: 40° emission angle; Exp. 5.4: 20° saccades between signs	Exp. 5.2: 4 participants (1F, 3M), 30–34 years, 32 years on average; Exp. 5.3: 10 participants, 22–35 years, 31 years on average; Exp. 5.4: 55 participants (<25 to 40 years); Exp. 6.2: 5 participants (3F, 2M), 26–55 years; Exp. 6.3: 16 participants (<20 to >60 years)	LED centered in a white circle on a dark background; Practical Setup
Wang et al. (2017) [49]	400, 1200, 2000, 3000, 4000, 5000 Hz	90 cd/m ²	White	Modulation depth: between 0 and 100%	Sinus	20° and 40° Saccades; Angle width: 0.17°	15 participants (7F, 8M), 22–26 years, 26 years? on average	Black screen with two simultaneously glowing LED points
Lee et al. (2018) [23]	Exp. 1: 10 frequencies from 50 to 3000 Hz; Exp 2: 11 frequencies from 100 to 4000 Hz	0.07 lx at the eye and 253 cd/m ² at 50 cm distance	Red	X	X	40° Angle width; Saccades more than 70°	Exp1: 11 participants (2F, 9M), 22–32 years, 28.7 years on average; Exp 2: 10 participants, 25–32 years	Gray rotating disk with a red LED light point; speed: 0–298°/s

Table 3. Cont.

Reference	Frequency	Illumination	Chromaticity	Modulation Depth/Duty Cycle	Waveform	Angle	Number, Age and Gender	Experiment
Lee et al. (2019) [50]	10 frequencies from 60 to 1800 Hz	25, 100, 400 cd/m ²	430 to 670 in 10 steps	X	X	X	X	Special device with filters
Wang et al. (2019) [51]	100, 600, 1200 Hz	250 lx on the table	White stripe on a black background	Modulation depth: 20, 30, 50, 70, 100% (except at 600 Hz: 8, 10, 12, 15, 20%)	Sinus	Saccades 50°	20 participants (10M, 10F) 22–26 years	Illuminated line
Brown et al. (2020) [52]	Between 1–13 kHz and 60 kHz	10,000 cd/m ² light, low illuminance (<1 cd/m ²)	White (Red, Green)	X	Rectangle	Saccades 29°	Exp 1: 14 participants, 21–50 years; Exp 2: 38 participants (19F, 19M), 21–48 years	Black screen with a slit for the LED behind it
Park et al. (2020) [53]	500 Hz initial with 200 Hz interval jumps	25, 100, 400 cd/m ²	Red, Green, Blue: 631, 531, 455 nm	Modulation depth: 100%; Duty cycle: 50%	X	Saccades: 45°; Exp 1: Angle width: 0.25° and 0.5°; Exp 2: 11 widths between 0.125° and 8°	Exp 1: 26 participants (13F, 13M), 22 years on average; Exp 2: 31 participants	Light behind a slit (11 different widths)
Wang et al. (2021) [54]	100, 600 Hz	50, 250, 500 lx	White stripe on a black background, typical office light (white)	5 modulation depths from 20 to 100%	Sinus	Saccades: 50°	20 participants (10F, 10M), 22–26 years, 24 years on average	White stripe on a black plate
Kang et al. (2023) [55]	1 kHz to 11 kHz in steps of 1kHz	Room < 1 lx, approximately 8660 cd/m ²	Red (631nm), Green (521nm), Blue (463nm), Warm white (2870 K) and Cool white (8883 K)	Modulation depth: 100%; Duty cycle: 50%	X	Angle width: 17°	20 participants (9F, 11M). One participant was in 50s, and the remainder in 20s	Colored light stripe; triangle of red and green LEDs for controlled triggering of saccades
Martinsons et al. (2023) [56]	80, 300, 600, 900, 1200 and 1800 Hz	50 cd/m ²	Red, Green, Warm white (2700 K)	Modulation depth: between 0 and 100%	Sinus	Angle width: 0.2° (horizontally) × 10° (vertically); Saccades: 55°	20 participants (9F, 11M), 19 and 32 years	8 rows of white LEDs are placed behind a thin vertical slit made from black foam boards
Kang et al. (2023) [57]	Between 1 and 11 kHz in steps of 1 kHz, and 60 kHz	8600 cd/m ²	Cool white	Modulation depth: 100%; Duty cycle: 50%	X	Exp. 1: Saccades: 15°, 30°; Exp. 2: Angle width: 17°	21 participants (10F, 11M), all participants are in twenties	Colored light stripe; triangle of red and green LEDs for controlled triggering of saccades

Table 3. Cont.

Reference	Frequency	Illumination	Chromaticity	Modulation Depth/Duty Cycle	Waveform	Angle	Number, Age and Gender	Experiment
Kang et al. (2024) [58]	Frequency automatically calculated according to the weighted up–down method and 60 kHz	24,700 cd/m²	Warm white (2880 K)	Modulation depth: 100%; Duty cycle: 50%	Square	Saccades: 30°	14 participants (5F, 9M), 19–25 years	A slit in the front of the LEDs
Miller et al. (2024) [41]	From 90 to 6000 Hz	38,700 cd/m²	2871 K	Modulation depth: 0 to 100%; Duty cycle: 10, 30, 50%	Rectangle and Sinus	Exp. 1: Saccades: 44°	36 participants (15F, 20M and 1 non–binary), 19–76 years	An LED was set up on a draped cart
Miller et al. (2024) [59]	Sinus: 120, 400, 800, 1200, 2400 and 4800 Hz; Rectangle: 120, 400, 800, 1200, 2400, 4800 and 10,000 Hz	52,400 cd/m²	2871 K	Sinus: Seven or eight modulation depths (100%, 85%, 70%, 55%, 40%, 25%, 15% and 5% for 2400 Hz and less; 100% for 7000 Hz; 55%, 100% for 10,000 Hz) Rectangle: Modulation depths (100% and 55%), duty cycles (10% and 50%)	Rectangle and Sinus	Saccades: 22.5°	55 participants (53% are female), 22–81 years	An LED was set up on a draped cart
Tan et al. (2024) [60]	From 90 to 6000 Hz	38,700 cd/m²	2871 K	Modulation depth: 0 to 100%; Duty cycle: 10%, 30%, 50%	Rectangle and Sinus	Saccades: 44°	36 participants (15F, 20M and 1 non–binary), 19–76 years	An LED was set up on a draped cart

3.1. Stroboscopic Effect—General Overview

Studies on the stroboscopic effect primarily investigate the limits for the perception of the effect depending on different parameters. Furthermore, the development of metrics to quantify the effect and its impact on humans are central topics of current literature. In general, there are various parameters that affect the perception threshold frequency. An example of stroboscopic effect is shown in Figure 5.

Bullough et al. (2011) conclude from their experiments that the perception of the effect depends not only on light modulation frequency, but also on the modulation depth and the duty cycle, where the duty cycle is defined as the fraction of one period during which the signal is ON [24]. The effect is generally perceived more strongly with high modulation depth and low frequency in a direct comparison with flicker. The authors also investigated the effect of waveform and correlated color temperature (CCT), but no significant differences were found in this regard.

In a follow-up study, Bullough et al. (2012) investigated the relationship between modulation frequency and modulation depth (as percent flicker) and expressed these in a combined function in order to gain a better understanding of the interaction between the two parameters [25]. The authors conclude that both parameters interact with each other, thus providing a basis for further research. However, the equations are only valid for a duty cycle of 50%.

Beyond the threshold where the effect becomes slightly noticeable, the extent to which the effect is perceived as disruptive is also considered. In the latter scenario, participants no longer perceive differences in modulation beyond 1000 Hz as intrusive, even though the distinctions remain detectable at higher frequencies [24,25].

Tu et al. (2013) explored the impact of frequency on the stroboscopic effect among Chinese and European subjects [26]. The findings indicate that the visibility of the stroboscopic effect diminishes with increasing frequency and becomes imperceptible beyond 750 Hz. No significant variances were observed between Chinese and European subjects under comparable experimental settings, suggesting a lack of cultural disparities in sensitivity to the effect's perception.

In his doctoral thesis, Polin (2015) examined the impact of various parameters in conditions that were derived from an office setting. Within these parameters, he discovered that the stroboscopic effect is identifiable at frequencies up to 700 Hz, while subjects begin to tolerate the effect at 600 Hz, thus recommending to use frequencies above 550 Hz. In addition to frequencies tested, factors such as the age and gender of the subjects, their current emotional state and the time of day also significantly impact the outcomes. Individuals under the age of 26 were less likely to notice the effect. Age plays a more significant role than gender in this context. Although men can perceive the effect at higher pulse width modulation frequencies, women were comparatively insensitive. However, substantial individual variances in perception remain unexplained by the aforementioned factors [29]. Furthermore, the author proposed a control strategy for LEDs to consciously mitigate the effect without the necessity of increasing frequency. By implementing a strategic phase shift in the LED controller, the perception of a temporally continuous light source was maintained [29,31].

Wang et al. (2015) affirmed that the detectability of the stroboscopic effect is contingent upon factors such as frequency, illumination level, waveform and the velocity of the moving object [28]. As frequency increases, a greater modulation depth is required for the effect to be perceived by 50% of the subjects. When plotting the visibility threshold against modulation depth and duty cycle, a U-shaped relationship emerges, with a minimum at 30% modulation depth and an illuminance between 10–100 lx. Sensitivity to the effect also increases with the object's velocity.

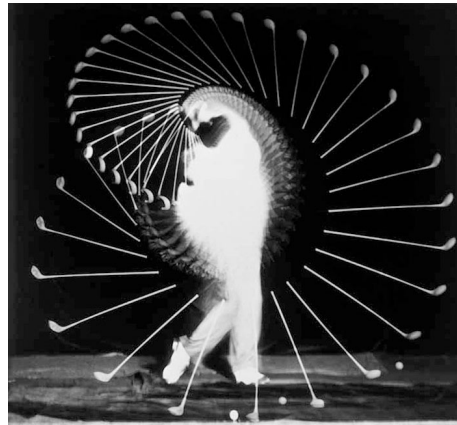


Figure 5. A demonstration of the stroboscopic effect in the golf swing. Source from: Harold Eugene Edgerton, “Golfer”, The Museum of Modern Art (MoMA) collection, accessed via <https://www.moma.org/collection/works/44219> (accessed on 3 June 2026).

In 2016, Bullough et al. extended the investigation to examine how different waveforms, frequencies, duty cycles, percent flicker and flicker indices affect the visibility of the stroboscopic effect [30]. The authors aimed to reconcile discrepancies in prior research and enhance the understanding of the effect’s influencing parameters by comparing various flicker characteristics and waveforms. They argued that the flicker index is a more appropriate metric than percent flicker and introduce a modified flicker index to make signals of disparate waveforms comparable. In 2023, Miller et al. analyzed the visibility of stroboscopic effects under 74 waveforms [41]. The results showed the stroboscopic effects peaks between 90 Hz and 120 Hz and becomes more visible under rectangular versus sinusoidal TLM, higher modulation and when duty cycles are 10% or 30% versus 50%.

In order to define a suitable metric for the stroboscopic effect, Perz and Wang et al. (2015) conducted a study with three experiments that formed the basis for the development of the SVM and also demonstrated the validity of the newly developed metric [27,28]. The underlying concept is based on the theory of frequency summation, which states that the visibility of the stroboscopic effect can be assumed to be the sum of the energies of all Fourier components of a given waveform, adjusted for human sensitivity. To validate the SVM, Perz et al. (2018) conducted additional tests with more subjects and frequencies, thus allowing us to introduce the standard observer for the SVM metric. Furthermore, the authors also tested how different lighting levels affect and thereby make the SVM relevant for use in different lighting situations [32,34].

The SVM can be expressed as:

$$\text{SVM} = \sqrt[3.7]{\sum_{m=1}^{\infty} \left(\frac{C_m}{T_m} \right)^{3.7}}, \quad (1)$$

where C_m denotes the amplitude of the m -th Fourier component, and T_m represents the visibility threshold for stroboscopic effect for a sine wave at the frequency of the m -th Fourier component.

The SVM represents the most widely adopted standardized metric for evaluating stroboscopic effect visibility in LED lighting systems. It is based on Fourier decomposition of temporal light modulation signals combined with human contrast sensitivity weighting.

In practical applications, SVM provides a single scalar value that enables comparison between different LED drivers, waveform conditions, and dimming strategies. Regulatory discussions, including industry adoption thresholds, have led to its use as a design guideline in lighting engineering practice. However, its validity is primarily established

under high illuminance laboratory conditions, and its applicability in low-light or dynamic real-world environments remains limited.

To account for human visual sensitivity, each normalized amplitude is weighted by dividing it by the temporal contrast sensitivity function (TCSF) at the respective frequency. The TCSF describes the threshold contrast required for the human eye to detect flicker or modulation at different temporal frequencies [61]. It is commonly modeled by the following empirical function:

$$T_V(f_{SE}) = 2.865 \cdot 10^{-5} \cdot f_{SE}^{1.543} + 0.225 + 20 \cdot e^{-f_{SE}/10}, \quad (2)$$

where f_{SE} is the visibility threshold of stroboscopic effect.

Figure 6 shows the temporal contrast threshold function of the stroboscopic effect. The solid line corresponds to the power function, as defined in Equation (2). The black dot depicts the highest frequency at which the stroboscopic effect can be detected, 1280 Hz, in application contexts as detailed in [32,34]. The dotted line is an extrapolation of the power function to the higher frequencies. Note that the temporal contrast threshold function can also be represented in terms of the temporal contrast sensitivity.

Furthermore, Tan et al. (2024) analyzed TLM visibility metrics and their sensitivity to sampling rates [42]. While the stroboscopic visibility measure remained stable within defined ranges, metrics like the short-term flicker severity value P_{st}^{LM} showed greater variability.

Since LEDs are used in environments where their light can also affect the health and well-being of people in these spaces, Zhao et al. (2018) investigated the effects of pulse-width-modulated LED light above the flicker frequency on people in an office environment [33]. The authors explored changes in Electroencephalogram (EEG) brain waves, pupil sizes, critical flicker fusion frequency and participant fatigue. Measurements before and after performing various tasks showed effects on participant fatigue. Furthermore, changes in brain waves in the occipital lobe were detected, suggesting alterations in neural activity that may be associated with consciousness. Zhao et al. (2019) examined in a subsequent study to evaluate the impact of different SVM values on cognitive performance [36]. The authors established a significant, qualitative relationship between cognitive performance and the SVM level. Higher SVM values lead (in addition to an increased perception of the effect) to more nervousness and poorer perception and concentration in the conducted experiments.

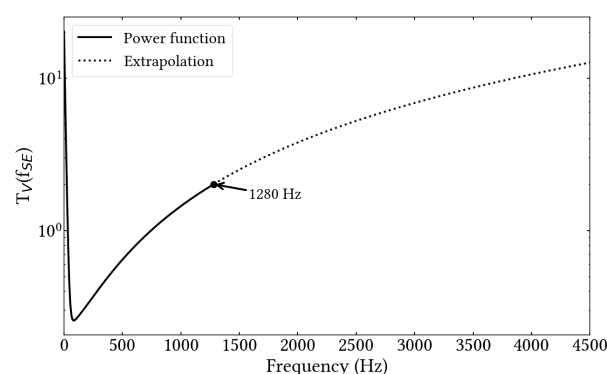


Figure 6. Temporal contrast threshold function that could be used to compute the stroboscopic effect visibility measure, as detailed in Equation (2). Data adapted from Perz et al. [34].

Furthermore, Zhao et al. (2020) investigated the short-term consequences of stroboscopic light on individuals under more intense conditions [40]. Participants significantly perceived the discrete spatial movement and found the effect uncomfortable under these conditions. Additionally, participants become increasingly fatigued. Fatigue is indirectly

measured via the critical flicker frequency (CFF). A higher CFF indicates a decrease in participant sensitivity and thus they are likely experiencing more fatigue.

In addition to the short-term effects mentioned above, people who are exposed to modulated light over a longer period of time can suffer from the effects of long-term exposure. Sekulovski et al. (2020) provided initial findings for these long-term consequences [38]. The perception of the subjects was investigated in a realistic work scenario under moderate lighting conditions. The authors found no significant effect and conclude that the likelihood of a slight increase in complaints is below 5%.

In 2024, Veitch et al. examined the effects of temporal light modulation on visual and cognitive performance [43]. They found that 100 Hz modulation led to increased pupil size and greater event-related potential (ERP) dipole strength, particularly in the right hemisphere. Cognitive interference was lower under 500 Hz than 100 Hz, while state anxiety remained unaffected. Subsequently, Kang et al. (2024) examined the effects of temporal light modulation from LED lighting on visual task performance under five conditions [44]. Their findings indicated that tasks requiring extensive eye and object movements, like number-linking, were more influenced by stroboscopic visibility, emphasizing the role of stroboscopic effects.

In 2025, Zhao et al. investigated the psychological responses to temporal light modulation in office environments using the stroboscopic visibility measure [45]. This study found that higher SVM levels increased stroboscopic visibility and motion dispersion, negatively impacting visual comfort, cognitive performance and work efficiency, while showing limitations in predicting eye saccade effects.

Veitch et al. (2019) emphasized that knowledge about the consequences for health and productivity is also an essential basis for future policy decisions regarding limits and regulations [35]. To gain more understanding of different SVM values and the associated perception, subjects at two different locations (France and Canada) were surveyed. The results showed that nearly everyone can perceive the stroboscopic effect with an SVM value greater than 2 and about one quarter of all young Europeans can perceive the effect with a value of 1.4. Only very sensitive individuals (10%) perceived the stroboscopic effect with an SVM value of about 0.4.

Several studies report substantial inter-individual variability in perception thresholds, with some sensitive observers detecting the effect even under conditions where most participants no longer perceive it [29,34].

Veitch et al. (2020) stated that participants with higher sensitivity do not necessarily have a better perception of the effect, they are more annoyed by the effect compared to participants with comparatively lower sensitivity [37].

To enhance comprehension of the diverse perceptual responses among participants, Apriyandi et al. (2020) devised a methodological approach within their experimental framework to interrogate the subjective certainty with which subjects report the observation of the effect [39]. Diverging from conventional binary response models, the researchers instituted a nuanced five-point scale enabling participants to articulate their perceptual experience with graduated levels of assurance. This scale ranges from 'with absolute certainty' to 'sure', 'uncertain', 'possibly', and 'not at all', thereby facilitating a more refined analysis of perceptual variance among individuals.

While the research objectives vary by study, the aforementioned results are based on data that can be obtained through participant involvement in laboratory investigations. Ku et al. (2015) provided an approach to investigate the stroboscopic effect using mathematical simulations [62]. For example, this approach enables the evaluation of lamp performance without requiring participant involvement in the testing process. Furthermore, the simulation approach allows the examination of different waveforms (rectangular, sinusoidal, etc.) in terms of their impact on the stroboscopic effect.

Kobav et al. (2018) described, designed and tested a standardized experimental setup to test various settings for power supply and signal properties, allowing us to compare the results for different light sources [63]. The authors also pointed out that there were very few standardized measurement methods for this effect at that time.

Despite methodological differences, recurring parameter trends can be identified across studies, as summarized in Table 2.

3.2. Stroboscopic Effect—Experimental Setups

The most commonly used setup for detecting the stroboscopic effect consists of a black, rotating disk with a white dot. When the disc rotates under conditions favorable to the effect, the observer perceives a pattern of several white dots along a circular path (see Figure 7). Tu et al. (2013) used a 27 cm diameter disk with a 2.6 cm white dot [26]. The disk was positioned on a table and rotated at a speed of 4 m/s to replicate the maximum speed that can be generated by the movement of a human hand. Similarly, Perz et al. (2015) used an identical setup in their studies, but with an additional 5 cm elevation of the disk [27]. According to their description, this increase corresponds approximately to the typical height of a standard table. The horizontal illuminance on the table surface was measured at 500 lx with a correlated color temperature of 4800 K. In their 2018 follow-up experiment, the authors added that the black surface has a reflectance of 7%, while the white dot reflects 81%, giving a contrast ratio of 12:1. The same experimental setup was also used by Wang et al. (2015), Polin et al. (2017), Veitch et al. (2019), Apriyandi et al. (2020) and Zhao et al. (2025) [28,31,35,39,45].

In addition to the horizontal turntable, a vertical device was also used to determine whether there were differences between horizontal and vertical light conditions. Veitch et al. (2020) used a mechanical metronome for this purpose, which ticked at a frequency of 208 beats per minute and had a black dot at the top of the pendulum [37]. Similarly, Bullough et al. (2016) attempted to detect the stroboscopic effect in a vertical scenario by using a metronome covered with white paper [30]. The pendulum of the metronome, with a length of 14 cm, moved at 3.5 Hz and spanned a maximum angle of 120°. Subsequently, Miller et al. (2023) used a white wand with a tangential velocity of 4 m s⁻¹ in their experiments [41].

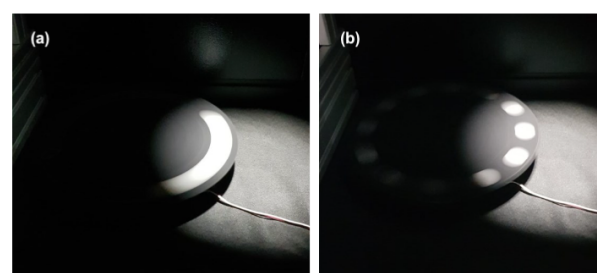


Figure 7. (a) A rotating disk as typically used in experiments to detect the stroboscopic effect. The disk is illuminated by a continuous (unmodulated) light source with a duty cycle of 100%, resulting in a steady visual perception without visible afterimages. (b) The same disk under a temporally modulated light source. Due to the intermittent illumination, multiple afterimages become visible, illustrating the stroboscopic effect.

In addition to a large number of laboratory studies designed to characterize the influence of certain parameters on the perception of the stroboscopic effect under controlled test conditions, the impact of pulse-width-modulated LED lighting on the perception of the stroboscopic effect was investigated in scenarios that were as realistic as possible. Sekulovski et al. (2020) utilized two working environments: an electronics workshop and an open workspace, each illuminated with modulated light sources operating at different

SVM values [38]. Rather than deliberately triggering the stroboscopic effect, the long-term impact on individuals working in these spaces was examined. Similarly, Polin et al. (2015) have chosen a realistic setup resembling an office environment where participants were asked to perform various tasks, including swinging a cable mouse over a laptop, counting words on a sheet, shading a square, and moving the hand back and forth as quickly as possible [29]. Bullough et al. (2011) employed a realistic setup to investigate not only the stroboscopic effect but also flickering [24]. In their setup, participants were seated at a table in a dimmed room equipped with a controllable modulated lamp, a laptop for simple calculations and a notepad for answering specific questions. To study the stroboscopic effect, participants were asked to move their hands back and forth under the light source.

A nearly identical setup was used in a follow-up study by the authors, where instead of moving their hands, participants were asked to wave a white plastic rod (after an introduction to keep the movement as uniform as possible). Additionally, unlike in the previous study, the computer was turned off [25]. In a subsequent study, participants were asked to move a white ruler back and forth as quickly as possible [30]. The experimental methods vary considerably across studies, particularly regarding movement tasks and fixation control. Miller et al. (2023) speculated that the stronger perception of the effect in Bullough et al.'s results compared to similar studies using a rotating disk could be attributed to the arbitrary movements being performed faster and covering a wider visual field [4]. Furthermore, the eye position was not fixed on a fixation point.

In addition to the rotating disk, Zhao et al. (2019) also employed two concentration tests to assess the correlation between SVM values and cognitive performance [36]. In a subsequent study, the rotating disk experiment was complemented by surveys assessing fatigue using the visual analogue scale for fatigue (VAS-F) and emotional state using the positive and negative affect schedule (PANAS). Furthermore, Anfimov's table and a transcription task were employed as concentration tasks, in addition to the recording of EEG values, pupil size and the critical flicker fusion frequency [40]. Subsequently, Veitch et al. (2023) employed two cognitive performance tests (the sentence reading task and the Stroop task) [43]. Furthermore, they investigated the influence of stimuli on state anxiety, eye movements and visual ERPs. In 2024, Kang et al. assessed participants' performance in various visual tasks involving eye movements, including arithmetic problem-solving, linking numbers tasks and the CamBlobs Contrast Sensitivity test [44]. Zhao et al. (2025) investigated the relationship between temporal light modulation and potential psychological responses using the stroboscopic visibility measure [45]. They evaluated subjective general ratings, the observation of moving objects, sustained attention visual tasks, visual fatigue and emotional state using PANAS. In the experiments conducted by Ku et al. (2015), a white line (a 9 mm wide strip of white paper) is used on the black disk instead of a white point, extending from the outer edge of the disk towards its center [62]. The disk rotates at 12 Hz. However, no human subjects were used; instead, a camera was employed to detect the effect. Kobav et al. (2018) designed two test boxes that allow different LED light sources to be adjusted, thus allowing the observation and comparison of temporal light artifacts under controllable settings [63].

3.3. Stroboscopic Effect—Experimental Procedure

Apart from three articles that do not focus on subject studies [42,62,63], the remaining articles include subject-based studies. In addition to the experimental design, variations with regard to the subjects and the procedure of the experiments themselves are compared.

Where subjects studies were conducted and information about the subjects is provided (no details are provided by Wang et al. (2015) [28]), most studies utilize a minimum of 10 participants. Six studies, conducted by Bullough et al. (2011, 2012, 2016) and

Zhao et al. (2018, 2020, 2025) regarding the stroboscopic effect, employ exactly 10 test subjects [24,25,30,33,40,45]. Seven studies employ more than 10 but fewer than 30 test subjects [26,27,31,32,34,38,39]. Three studies employ more than 30 test subjects [41,43,44]. In the study conducted by Sekulovski et al. (2020), initially almost 50 participants were recruited [38]. However, the results for each subjects was only valid if they completed the required questionnaires twice daily over the multi-week course of the experiment, resulting in significantly fewer test results being considered for actual analysis. Therefore, this study is represented here with fewer than 30 test subjects. In the remaining two studies, 36 subjects were surveyed by Veitch et al. in 2019 [35] and 85 subjects in 2020 [37]. Across all studies, the number of participants ranged from 10 to 85, with an average of 25 participants per study. Seven studies included more than 20 participants, whereas six studies were limited to exactly 10 participants.

It is also worth noting that, on average, almost twice as many men as women were tested (11.8 men compared to 6.7 women). However, it must also be emphasized that the study by Sekulovski et al. (2020) has a relatively extreme ratio of 42:4 between men and women, which could be considered an outlier [38]. Excluding this study, the ratio of all studies as a whole drops to just 9:7. Overall, about 57% of participants were male and 43% female. Excluding the outlier study by Sekulovski et al. (2020), the ratio across studies is closer to 56% male and 44% female [38]. This imbalance should be considered when interpreting results.

The age of the test subjects ranged between 19 and 76 years depending on the considered study, with a mean age of approximately 32 years. Some studies focused on younger adults, potentially limiting generalizability to older populations [27,38]. Participants with particular sensitivities were generally excluded from the experiments and only participants with good or corrected vision took part in the experiments.

While this study [27] suggests minimal cross-cultural variation, including more diverse populations in future studies could further confirm the generalizability of these results.

In order to determine the perception threshold, the stimuli were presented to the test subjects randomly (constant stimuli method) or systematically (staircase method) [26,32,36]. In some of the studies, a test light source was compared with a reference light source, whereby the test subjects had to decide within a few seconds whether a difference between the two light sources could be perceived [26,28,32]. Depending on the number of parameter combinations to be tested, the duration of the tests varied for the test subjects. While Bullough et al. (2011) tested 9 parameter combinations (plus additional questions) within 20 min per subject [24], the experiments by Zhao et al. (2020) lasted around 5 h [40].

In addition to the determination of the detection threshold, some of the studies aimed at the acceptance of the effect. For this purpose, the test subjects used a scale to indicate how annoying the effect was perceived to be [25,30,35,37,45].

Both the stroboscopic effect and the phantom array effect come from modulated light, but they show up in different ways and need separate consideration. In the next section, we focus on research on the phantom array effect.

3.4. Phantom Array Effect—General Overview

Generally, most of the employed studies investigate the perception threshold of the phantom array effect in controlled laboratory environments. For example, when an eye saccade is made across a small point light source with a square periodic luminance modulation, the light source is perceived as a series of spatially extended light spots, as shown in Figure 8. In real-world scenarios, this can be the most readily observed when driving at night behind cars with LED rear lights, as shown in Figure 9. The experimental results show substantial variability in reported threshold frequencies across studies. In the fol-

lowing, the existing results on the phantom array effect are used to explain the impact of various parameters with regard to the evaluated threshold frequencies. Table 3 presents a comparison of the relevant literature with different parameters analyzed.

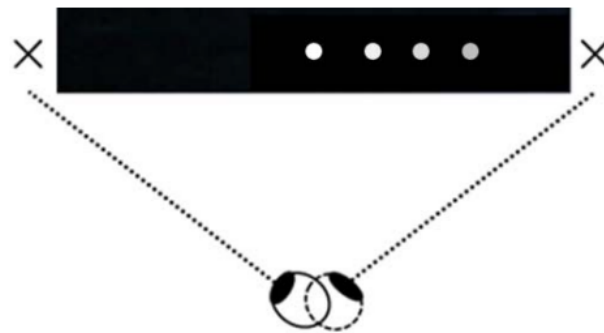


Figure 8. Illustration of the phantom array effect, adapted from Wang et al. [49]: when making an eye saccade from left to right across a temporally modulated point light source, in a dark environment, an array of dots will be perceived.



Figure 9. A demonstration of the phantom array effects in the car light [64]. Adapted from James M. Gaines, Illuminating Engineering Society (IES).

Hershberger and Jordan explored the threshold frequency for the effect in 1998, concluding that the effect is perceivable for frequencies up to 500 Hz. However, it is important to highlight that 500 Hz was also the highest frequency tested [46]. Roberts and Wilkins (2012) employed higher frequencies in their experiments and identified a threshold frequency of 2000 Hz with a comparable bright line-shaped stimulus (150 cd/m^2) and saccades between 20° to 40° [48]. Brown et al. (2019) investigated the visibility of the effect for even higher frequencies between 1–11 kHz [52]. On average, participants detected the phantom array effect up to 6 kHz, which increases the threshold frequency derived from this study by a factor of two compared to previous studies. It is particularly noteworthy that a few participants even perceived the effect at 11 kHz. Participants who were able to reliably perceive the effect at these frequencies stated that they suffered from eye problems in their daily lives. Therefore, the effect becomes less visible as the frequency increases [47]. Martinsons et al. (2023) investigated the effect of temporal frequency on the visibility of the phantom array effect, but with a special interest in how the peak frequency changes with chromaticity [56]. They found that the sensitivity to the phantom array effect follows a bandpass-shaped function, peaking at 600 Hz. Subsequently, Kang et al. (2024) investigated the highest frequency limit of the phantom array effect by estimating the participant's threshold frequency for the visibility of the phantom array effect using the weighted up-down method [58]. The mean threshold frequency for young adults was approximately 10 kHz. The phantom array effect was observed even above 15 kHz in the participant group of high threshold frequencies. A lower modulation depth also affects the threshold frequency. In the studies reported by Roberts and Wilkins (2012), a

modulation depth of 10% resulted in a no longer perceptible effect, independent of further tested experimental parameters [48].

The effect also becomes less visible as the duty cycle increases and the illuminance decreases [47]. The impact of illuminance is also more closely analyzed by Wang et al. (2021) [54]. At a frequency of 100 Hz, the authors note no significant difference between various illuminance levels. However, as the frequency rises up to 600 Hz, the phantom array effect is increasingly perceived at higher levels of illuminance [54].

Park et al. (2020) [53] further investigated the dependence of the effect on the brightness of the light stimulus. The authors concluded that the threshold frequency increases proportionally to the logarithm of the brightness/luminance of the light source [53]. Lee et al. (2018) also confirmed that higher luminance contributes to an increase in the threshold frequency [23].

Miller et al. (2024) explored the visibility of the phantom array effect with targeted tasks under 74 TLM waveforms [41]. The authors concluded that the effect has visibility peaks between 500 Hz and 1000 Hz, with highly sensitive participants perceiving the effect even at 6000 Hz. This effect is more visible under rectangular and sinusoidal TLM, higher modulation and when duty cycles are 10% or 30% versus 50%.

The beam size also affects the detectability of the phantom array effect. The effect becomes less visible as the beam size increases. Vogels and Hernando (2012) further reported that the effect is best perceived when the light source is as small as possible and forms a sharp transition to the surroundings at the edges of the light source [47]. Wang et al. (2017) explored the relationship between modulation frequency and saccade amplitude in terms of the effect's visibility [49]. In their studies, 50% of participants still recognized the effect at 2000 Hz. At 3000 Hz, the effect disappeared. In their experiments, the perception thresholds for low frequencies were not affected by saccade amplitudes. The laboratory studies by Polin et al. (2015) indicate that the threshold frequency for horizontal saccades is comparatively higher than for vertical saccades [29]. Park et al. (2020) further examined the dependence of the effect on the angular width of the field of view [53]. With a greater field of view (0.125° to 4° tested), the threshold frequency decreases exponentially. Kang et al. (2023) investigated the relationship between saccadic eye movement speed and phantom array visibility at two different angles and four different directions of saccadic eye movement [57]. The findings show that phantom array visibility increased as eye movement speed increased, and the phantom array visibility was higher at a wide viewing angle with fast eye movement speed than at a narrow viewing angle.

The color of the light source used is also a relevant parameter for the phantom array effect. The studies by Park et al. (2020) indicated that the threshold frequency depends on the wavelength of the light source used for high modulation frequencies [53]. In their experiments, the blue light source produced a lower threshold frequency compared to red and green. In 2019, Lee et al. (2019) determined a function for contrast sensitivity depending on the critical flicker fusion frequency and the wavelength for the perception of the effect [50]. The results indicated that contrast sensitivity depends on both the color and ambient brightness for high as well as moderate modulation frequencies.

Since phosphor-converted white LEDs can exhibit a wide range of correlated color temperatures, the authors extended their research for frequencies ranging from 1 kHz to 11 kHz. They confirmed their previous findings and concluded that the threshold frequency is increasing continuously from blue to cool white to red to warm white and to green light situations. Thus, the sequence shows that the dominant wavelength (more blue for cooler and more red for warmer light sources) has a systematic effect on the threshold frequency [55]. Polin (2015) stated in their comparison of blue (450 nm), green (520 nm), and red light (625 nm) that the phantom array effect is more likely to be perceived with

green light than with red light. With blue light, the test subjects were no longer able to perceive the effect. The author suspected that this is due to the distribution of cones on the retina [29].

In 2023, Martinsons et al. investigated the effect of chromaticity on the visibility of the phantom array effect [56]. The authors found that the peak frequency of the sensitivity function remained unchanged across different chromaticities, although the visibility threshold varied with color.

In order to test the perception of the effect in realistic scenarios, Wang et al. (2019) conducted analogous experiments in office lighting situations [51]. In the chosen indirect lighting scenario, participants perceived the effect of a thin white strip on a black surface at about 600 Hz on average. A black target on a white background, similar to the scenario when reading, triggers the effect with lower probability [51]. Polin et al. (2015) also investigated the impact of various parameters on the perception of the Phantom Array Effect, focusing specifically on automotive lighting situations [29]. As part of his dissertation, the author conducted four participant studies in a controlled laboratory environment and two trials in road traffic. In these situations, the effect can be triggered when the dimmed front light is reflected by traffic signs or other reflective surfaces along the roadway. The laboratory studies showed that the effect can still be triggered at frequencies of 1000 Hz. The 50% threshold frequency is located at approximately 570 Hz. A comparison with the results obtained under real conditions shows that the threshold frequency in real road traffic is slightly lower (460 Hz). The reason for the difference between laboratory tests and investigations in road traffic may be that the driver is more focused on traffic and driving itself and not solely on the effect as in a controlled laboratory environment.

When comparing typical road traffic lighting conditions with the standard definitions of the phantom array effect and the stroboscopic effect, the combination of moving light sources and saccadic eye movements can be conceptualized as a new phenomenon: the stroboscopic–phantom array effect. This effect refers to a perceptual artifact that emerges when temporally modulated moving light sources are observed during saccades, often resulting in spatially discrete or multiple image patterns due to the interaction of temporal light modulation, eye motion, and source movement. Lee et al. (2018) investigated this combined effect using a rotating disk equipped with a red LED instead of a white point (Section 3.2) [23]. Their study demonstrated that the detectability threshold of the stroboscopic–phantom array effect is primarily determined by the relative speed between eye movements and light source motion, rather than by either factor individually. Additionally, their findings show that moving modulated light sources can produce stroboscopic-like artifacts even during fixed gaze, while the simultaneous occurrence of saccades and source motion significantly amplifies the effect. This interplay underscores that the stroboscopic effect and phantom array effect (PAE) cannot always be treated independently in dynamic real-world scenarios.

Miller et al. (2024) investigated the phantom array effect with 55 test subjects, including 25 with migraines and using 85 temporal light modulation waveforms [59]. Migraine sufferers exhibited higher phantom array visibility, greater sensitivity at higher frequencies, and increased annoyance and physiological discomfort. After the experiment, 64% of the migraine group experienced discomfort, with 41% reporting headaches, compared to 19% and 8% in the non-migraine group, respectively.

The study by Tan et al. in 2024 presented a new measure, the phantom array visibility measure (PAVM) to quantify PAE visibility [60]. PAVM can be expressed as shown in Equation (3).

$$\text{PAVM} = \sqrt[2.1]{\sum_{m=1}^{\infty} (C_m \cdot S_m)^{2.1}}, \quad (3)$$

where C_m is the amplitude of the m -th Fourier component of a temporal light modulation (TLM) waveform divided by the DC value of the waveform, and S_m is the visibility sensitivity value for a sinusoidal wave at the frequency of the m -th Fourier component, calculated from a time-domain threshold visibility function.

The PAVM model is based on data from 36 participants without migraine, who rated the visibility of PAE on a 0–6 scale. A total of 74 TLM waveforms were tested, including 61 rectangular waveforms (ranging from 90 Hz to 6000 Hz, with varying modulation depths and duty cycles), 10 sinusoidal waveforms (including one at 120 Hz with 20% modulation), and 3 DC conditions. Stimuli were presented as a point-like LED source with a luminance of $38,700 \text{ cd m}^{-2}$ and a visual angle of 0.06° at a viewing distance of 3 m, against a dark background (0.6 cd m^{-2} to 2.3 cd m^{-2}). Participants executed saccades of approximately 44° across the source. For analysis, the actual measured waveforms were used rather than the programmed signals.

The metric transforms the time-domain TLM waveform into its Fourier components, weights each by a frequency-dependent sensitivity function from human threshold data, and combines them using a Minkowski summation. The authors adjusted the scale so that a value of 1 denotes the just-visible threshold for roughly half of observers. Values below 1 indicate reduced detectability. Validation with 36 participants and 74 waveforms yielded a sensitivity peak near 700 Hz, whereas the CIE sensitivity curve peaks at around 750 Hz, as shown in Figure 10. This may be due to different viewing conditions and experimental protocols that underlie the two functions, or simply variation in the underlying sample of observers [60].

Moreover, in contrast to SVM, the formulation of PAVM is based on a different threshold determination approach. Instead of repeated measurements to establish individual visibility thresholds, the PAVM sensitivity function was derived from interpolated points corresponding to a 50% visibility probability across the participant sample. In addition, a conversion factor was applied to translate square-wave modulation into an equivalent sinusoidal representation. Consequently, the methodological differences introduce additional uncertainty in the comparability with SVM, and further research is required to define the sensitivity curve with greater precision and to better align the PAVM sensitivity function with those developed for SVM.

Unlike the stroboscopic effect, the phantom array effect lacks a widely accepted standardized metric. This is primarily due to the higher complexity of its perceptual mechanism, which depends not only on temporal modulation parameters but also on saccadic eye movements, viewing geometry, stimulus size, and luminance distribution.

In addition, existing studies use inconsistent experimental paradigms and different definitions of detection thresholds (e.g., 50% detection probability, subjective visibility rating, or forced-choice decisions), making cross-study normalization difficult. As a result, no unified sensitivity function has been validated across large heterogeneous populations.

The absence of a standardized evaluation framework for PAE has direct implications for LED manufacturing and lighting design. Without a unified metric, manufacturers cannot reliably predict user discomfort or visibility complaints across different usage scenarios. This leads to over-conservative design (excessive dimming or higher cost drivers) or underestimation of perceptual artifacts in real-world applications such as automotive lighting and display systems.

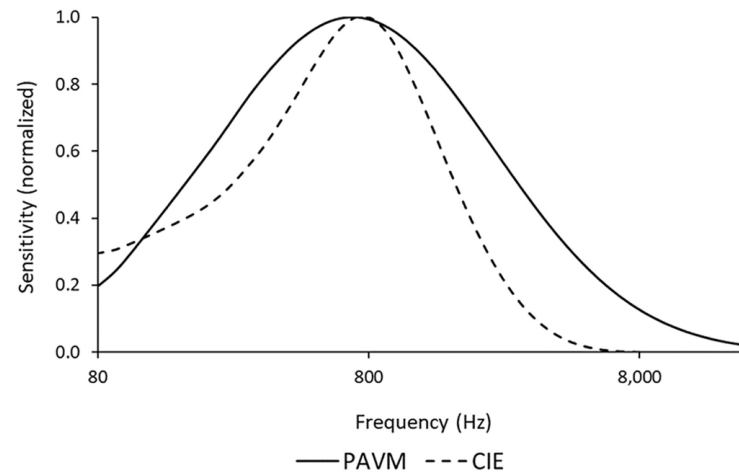


Figure 10. The normalized phantom array effect sensitivity curves derived from Miller et al. [41] (solid) and International Commission on Illumination (CIE) 249:202212 [61] (dashed). Source from Tan et al. [60].

3.5. Phantom Array Effect—Experimental Setups

The test setups that were used to evaluate the perception of the phantom array effect in the different studies show great similarities, but they differ in their subtleties. The effect is triggered when the subject looks directly at the light source, which is positioned between two fixation points. This positioning generates saccadic eye movements as the subject alternately looks at the different fixation points.

Roberts and Wilkins (2013), for example, used a black screen (2 m wide) in a darkened environment (<1 lx). Two white disks were attached to the edges of the screen as fixation points, between which the participants looked back and forth in order to perform controlled saccades. Two green lines appeared consecutively on the screen, one of which potentially triggered the phantom array effect. One line is generated with a continuous signal (therefore no visible effect), while the other line is stimulated with both a sine wave and a square wave signal at different frequencies (up to 5 kHz) [48]. Polin et al. (2015) investigated the phantom array effect under conditions relevant for automotive use cases, using miniature models and a practical test at a real road intersection to simulate more practical conditions in the lab [29].

Wang et al. (2017) used a similar setup, as shown in Figure 11, equipped with two white LED light points being switched on simultaneously and not one after the other [49]. Both the shape of the stimulus and the time delay differ here. Furthermore, the test subjects sit closer to the screen and their eye movements are monitored using an eye tracker.

Park et al. (2020) also used a similar setup to test the effect of various parameters, such as the angular width of the saccades performed by the subjects, color and brightness [53]. The experimental setup was adjusted for each parameter accordingly. The duty cycle was set to 50% at 100% modulation depth. The subjects were seated 1.6 m away from the light source. The geometry of the light source could be varied and was therefore not always a point light source. Vogels and Hernando (2012) created a vertical line using a black box placed in front of a lamp (24 white LEDs), which produced a white line through a slit in the box. The sharpness of the edges was varied with a diffuser [47]. Wang et al. (2019) adopted an alternative setup where the focus was not on the light source itself but on a white illuminated test strip [51]. The test strip was placed on a black table, which has two focus points at its edges, ensuring controlled saccadic movements similar to other experimental setups. The authors opted for this configuration to simulate a scenario of indirect lighting, analogous to conditions typically encountered in an office environment.

This same setup was also used in a subsequent study to examine the impact of brightness levels [54]. The studies by Kang et al. in 2023 used a compact and slim aperture that enabled the visibility of light in different colors. To control the velocity of the saccadic movements, a configuration of light points, illuminated in sequence and arranged in a triangular shape, was positioned surrounding the slit to guide the eye movements [55,57]. The study by Miller et al. in 2023 and 2024 used two 100 mm tall visual targets marked with an “X” on the wall for saccadic movements [41,59].

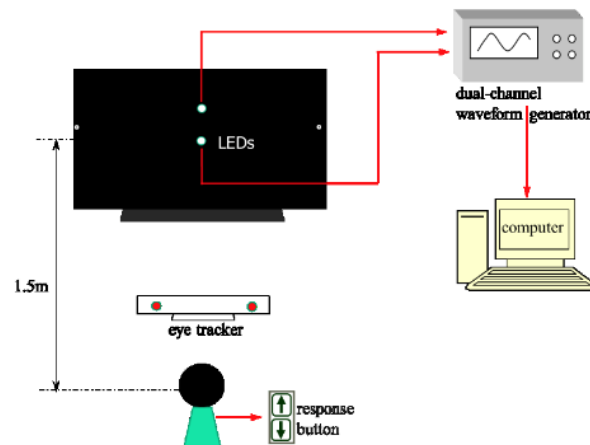


Figure 11. Experimental setup for phantom array perception. Two white LED dot sources were mounted in front of a black screen, with fixation points to elicit horizontal saccades. Eye movements were recorded using an eye tracker, while the LEDs were driven by a dual-channel waveform generator producing sinusoidal and Direct Current (DC) signals. Source from: Wang et al. [49].

Lee et al. (2018) explored the combined stroboscopic phantom array effect using a rotating disc, which had a red LED instead of a white point (compare with the experimental setup for the stroboscopic effect) [23]. As a result, neither the test subject nor the surroundings were static. Furthermore, a part of the disc was covered, limiting the subjects' view to only a proportion of the light path. Park et al. (2020) emphasized that in realistic scenarios, the gaze, the source, and the surroundings are rarely static [53]. Thus, the authors who analyzed the combined stroboscopic phantom array effect also considered more practically relevant scenarios [23].

3.6. Phantom Array Effect—Test Procedure

As presented in Table 3, the papers under consideration utilized between 3 and 55 participants, with a mean of approximately 22 participants per study. The publication by Lee et al. (2019) specified no participant number [50]. Roberts and Wilkins (2012) engaged three participants in their third experiment, representing the smallest cohort [48]. In two of the experiments by Polin et al. (2015) and Miller et al. (2024), the largest group was queried, consisting of 55 participants [29]. As shown in Table 3, most of the studies involve participants aged between 19 and 32 years. However, the study by Miller et al. (2024) also included older participants, up to the age of 81 years [59].

The gender distribution among participants is generally balanced or shows only slight differences. About 60% of participants were male and 40% female. In the studies by Vogels and Hernando (2012) and Kang et al. (2023), nearly twice as many men as women were recruited [47,58], whereas Roberts and Wilkins (2012) surveyed nearly twice as many women [48]. Excluding these outliers, the overall gender ratio is close to 1:1.

The descriptions of the participants highlight that they should not have impaired vision or should have corrected vision, for instance, using contact lenses [48], ensuring that the effect is not missed due to inadequate sight. Adequate visual acuity of the participants was checked with a Landolt ring, as in the experiments by Wang et al. (2017) [49]. Vogels and Hernando (2012) additionally excluded individuals wearing glasses and those suffering from epilepsy or migraines [47]. To rule out effects of achondroplasia, Park et al. (2020) employed an Ishihara color test [53]. Therefore, the focus in these studies was set on younger individuals without health restrictions and with nearly perfect vision. People who were particularly sensitive in their perception were also not included. An exception was a woman who reported using a green overlay when reading to make it more comfortable, this participant exhibited a significantly higher threshold frequency in the experiments compared to other subjects without visual impairments [48]. Brown et al. (2020) also confirmed that subjects reporting visual discomfort (e.g., dry, tired eyes or difficulty reading) tend to perceive the effect more readily [52], thereby highlighting the significance of including minority groups with unique sensitivities in such research.

Most studies were conducted in North America, Europe or China. No studies have specifically examined cross-cultural or regional differences in the perception of the phantom array effect. Future research could include more diverse populations to determine whether cultural factors influence sensitivity to this phenomenon.

Significant differences were observed in the details of the experimental procedures. Initially, it is noteworthy that the subjects were exposed to stimuli for varying lengths of time and numbers of test cycles. Depending on the parameters being tested, a multitude of combinations were used to isolate and examine the effect of each parameter. For example, Wang et al. (2019) employed three different frequencies and five modulation depths, resulting in 15 (3×5) different stimuli [51]. Each of these was repeated 10 times for every test subject. When multiplied by the number of stimuli, this amounts to 150 trials per participant, which the authors divided into three blocks of 50 trials each to prevent fatigue. In Kang et al.'s (2022) study, each participant underwent approximately 2.5 h of testing [55]. The study by Miller et al. (2024) used two waveforms, 7–8 modulation depths and two duty cycles, resulting in 85 different stimuli [59]. The experimental session lasted approximately 90 min.

Upon exposure to a specific stimulus, participants were asked to evaluate whether and how the effect was perceived. Depending on the experimental setup and methodology, the nature of this assessment varies. In setups where a light source that potentially triggers the effect was compared with a reference light source, participants were given a choice. After each trial, the participant had to decide between the two light sources, guessing if uncertain. Wang et al. use this so-called 2-Alternative Forced Choice (2AFC) methodology in their studies from 2019 and 2021 [51,54]. Similarly, Roberts and Wilkins (2012), Brown et al. (2020) and Kang et al. (2023) employed this approach [48,52,58]. The stimuli can either be presented in random order or controlled using a specific scheme [48]. For example, Wang et al. (2017) utilized a weighted up-down staircase method. At the start of each trial sequence, the maximum tested modulation depth was used [49]. Following each correct response, the modulation depth was decreased, and it was increased following each incorrect response. After several iterations, a stair-step pattern emerged when plotting the modulation depth across the trial sequences. Kang et al. (2023) used the weighted up-down method to ensure the step size of iterations [58]. Miller et al. (2024) used hybrid staircase and constant stimuli methods in their experiments [59].

3.7. LED Driver Technologies and Temporal Light Artifact Generation

The generation and severity of TLAs are closely linked to the characteristics of the driving circuitry used in LED luminaires. Most commercially available LED drivers employ PWM techniques to regulate luminous output due to their simplicity and high efficiency. However, variations in PWM frequency, control algorithm and topology can significantly influence the TLM waveform presented to the eye, thereby affecting the visibility of stroboscopic and phantom array effects. High-frequency PWM drivers operating above perceptual thresholds tend to reduce visible modulation, whereas low-frequency drivers increase the likelihood of perceptible artifacts [19].

Alternative driver approaches, such as hybrid dimming techniques that combine PWM with constant-current reduction or analog modulation, have been proposed and implemented in practice to achieve smoother dimming with reduced perceptual artifacts [65]. These hybrid schemes can mitigate the abrupt transitions inherent to traditional PWM and decrease the prominence of temporal discontinuities, although empirical data quantifying their impact specifically on stroboscopic and phantom array visibility remain limited. Furthermore, the specific topology of LED driver circuits, including the stages of power conversion and feedback control mechanisms, affects the fidelity of the modulated current waveform and thus the temporal behavior of the emitted light [6].

Optical components in the driver chain, such as filters, diffusers and lens systems, also interact with driver generated modulation to shape the final light output seen by the observer [66,67]. Appropriate optical design can spatially blend temporal fluctuations, reducing both subjective visibility and discomfort associated with TLAs in practical applications. Despite these advances, existing studies rarely isolate the influence of driver technology from other parameters such as duty cycle, modulation depth, and spectral properties.

3.8. Methodological Analysis Across Studies

Despite extensive experimental research on the stroboscopic effect and the phantom array effect, substantial methodological variability across studies limits the reproducibility and comparability of reported findings. A primary source of inconsistency lies in the definition of visibility thresholds, which range from simple detection to perceived disturbance or discomfort. As a result, threshold values reported for both effects often reflect different perceptual criteria rather than equivalent visibility levels. For example, Figure 12 illustrates representative perceptual appearances of the SE and the PAE. Both subfigures present a 0–6 visibility rating scale with reference examples ranging from “no visible” to “highly visible”, as used in psychophysical evaluation studies [41].

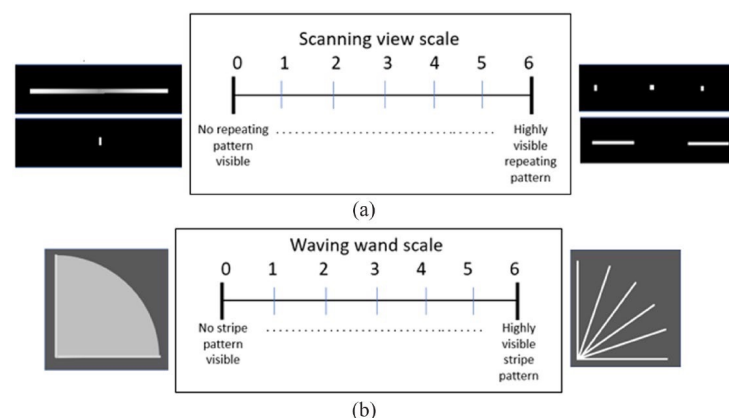


Figure 12. Representative perceptual evaluation framework for temporal light artifacts: (a) PAE; (b) SE, illustrative examples of perceptual visibility ratings (0–6) from “no visible” to “highly visible”. Adapted from Miller et al. [41].

Experimental stimulus configurations further differ considerably. While studies on the stroboscopic effect vary in stimulus motion, speed, trajectory and waveform characteristics, phantom array experiments employ diverse light source sizes, luminance levels, spatial arrangements and chromatic properties. Modulation parameters such as duty cycle, modulation depth and waveform shape are not consistently controlled or reported, despite their known influence on temporal light perception.

Observer factors are handled inconsistently across studies. In particular, phantom array experiments differ in their treatment of eye movements, with only a limited number of studies explicitly controlling or measuring saccades using eye-tracking systems. Individual sensitivity is sometimes treated as noise and averaged out, while other studies highlight extreme responders, complicating direct comparison.

Measurement approaches vary between subjective psychophysical methods and objective modeling techniques. Although predictive metrics such as the SVM have been proposed, systematic validation against experimental data remains limited, and no comparable metric exists for the phantom array effect. Collectively, these methodological differences represent a major barrier to reproducibility and the development of unified assessment frameworks for temporal light artifacts.

To facilitate practical application and experimental design, the objective parameters and subjective variables reported across the reviewed studies are summarized in Table 4.

Finally, situating these experimental and measurement approaches within the context of relevant international standards and regulations, as summarized in Table 5, provides a more comprehensive perspective on TLA evaluation in practical lighting applications.

While the results above describe empirical trends regarding parameters, thresholds and experimental conditions, the methodological inconsistencies, population biases, and metric limitations underlying these heterogeneous findings are synthesized in Research Gaps Section 4.

Table 4. Summary of variables related to temporal light artifact (TLA) studies.

Category	Variable	Role in Studies
Lighting Parameters (Objective)	Modulation frequency	Key determinant of flicker, stroboscopic and phantom array visibility
	Modulation depth	Strongly affects perceptual visibility and discomfort
	Waveform (e.g., sinusoidal, square)	Square waveforms often produce stronger stroboscopic effects
	Illuminance/luminance	Influences visibility thresholds and perceptual strength
	Spectral composition/CCT	More frequently studied for phantom array than stroboscopic effect
	Temporal light artifact metrics (e.g., SVM, P_{st}^{LM})	Used to quantify temporal light modulation and predict visibility
Stimulus Characteristics (Objective)	Stimulus speed	Major trigger of the stroboscopic effect
	Motion trajectory	Affects spatial distribution of perceived artifacts
	Contrast	Modulates detectability of temporal artifacts
Observer Visual Functions (Objective)	Visual acuity	May influence detection sensitivity
	Contrast sensitivity	Related to perception of temporal modulation
	Eye movement characteristics (e.g., saccade velocity)	Relevant for phantom array perception
	Visual field sensitivity	Potential contributor to inter-individual differences

Table 4. Cont.

Category	Variable	Role in Studies
Observer Characteristics (Subjective)	Age	Associated with temporal processing differences
	Gender	Occasionally reported in perceptual variability
	Physical condition/fatigue	May affect visual sensitivity and perception
	Migraine history	Linked to increased light sensitivity in some studies
	Circadian state/time of day	Influences visual and neurological responsiveness
Perceptual Outcomes (Subjective)	Visibility rating	Common psychophysical assessment of artifact perception
	Discomfort/annoyance	Evaluates perceptual acceptability of lighting
	Detection threshold	Indicates sensitivity to temporal light artifacts
	Qualitative perception reports	Descriptions of phantom array or stroboscopic impressions

Table 5. Summary of relevant international standards and regulations for TLA metrics.

Index	Defined By	Definition Point	Index Range
Percent Flicker	Illuminating Engineering Society (IES)	A relative measure of the cyclic variation in the amplitude of a light	0–100%; The lower the percent flicker, the less substantial the flicker.
Flicker Index	IES	A measure of the cyclic variation taking into account the waveform shape	0 to 1; The lower the flicker index, the less substantial the flicker.
P_{st}^{LM}	International Electrotechnical Commission (IEC) technical report (TR) 61547-1 IEC 61000-4-15	P_{st}^{LM} = ‘Short-term light modulation’ measures visible flicker	TLA in the frequency range between 0.3 Hz and 80 Hz. Index range is 0 to ∞ . $P_{st}^{LM} = 1$ is modulation that 50% of people can perceive. New European limiting value = 1.0
SVM	IEC TR 61547-1 IEC 61000-3-3 IEC 61000-4-15 International Commission on Illumination (CIE) technical note (TN) 006:2016 CIE 249:2022	SVM = ‘Stroboscopic Visibility Measure’ assesses stroboscopic effect which can occur in conjunction with moving objects	TLA in the frequency range from 80 Hz to 2000 Hz. Index range is 0 to about 8. SVM = 1 is modulation that 50% of people can perceive. New European limiting value = 0.4

4. Identification of Research Gaps

This section synthesizes the key unresolved questions identified from the reviewed literature and the preceding results, focusing on inconsistencies in experimental design, participant variability, parameter interactions and the limited validation of perceptual metrics for both the stroboscopic and phantom array effects.

4.1. Stroboscopic Effect—Fundamental Research

For addressing the research questions at hand, it is essential to pinpoint certain aspects that are fundamental for answering these questions, derived from the limitations and weaknesses of existing studies.

A pivotal element in basic research is the selection and number of test subjects. On the one hand, a certain quantity of participants is necessary to ensure the statistical significance of the data obtained. As demonstrated in Section 3.3, existing works often employ fewer

than 20 participants. Moreover, the results typically exhibit significant variances between subjects [29], which cannot be conclusively attributed to specific parameters and are more likely the outcome of complex biological interactions currently lacking clear explanations. Therefore, a recommendation would be to increase the number of participants and ensure more balance among age groups and genders, aiming to achieve more significant and balanced outcomes [37].

4.1.1.1. Key Parameters of the Stroboscopic Effect Perception

In general, a higher frequency tends to reduce the perception probability of the stroboscopic effect [24,27,28,30,32]. However, specifying exact frequencies must always consider the specific conditions or parameters used in the respective experiments [25]. Consequently, the discussion that follows will address additional parameters and their current state of research.

Particularly, reducing the modulation depth (e.g., from 100% to 33%) or the Percent Flicker value contributes to the effect being less noticeable [24,30]. Furthermore, the impact of modulation depth also depends on the frequency level. When the frequency substantially surpasses 100 Hz, a combination of increased frequency and reduced modulation depth results in participants being less likely to perceive the effects. Furthermore, at high frequencies, participants generally do not find the effect disturbing, almost irrespective of the modulation depth [25].

Plotting the visibility threshold as modulation depth over frequency while keeping the duty cycle constant reveals that even slightly different methodologies and stimuli can result in fundamentally different scales of results, although the basic effect remains. Perz et al. compared their findings with those of Bullough et al. under the aforementioned conditions, illustrating how the effect of a reference light and the use of a rotating disc instead of an individually moved rod can alter the outcomes [27].

Bullough et al. (2016) demonstrated that different visual tasks (metronome compared to ruler) under identical technical conditions show similar dependencies but different degrees of manifestation [30]. Hence, the visual task and its associated geometry also significantly affect the perceptibility of the effect. However, it is possible that the metronome was slower than the ruler movements, leading to less effective perception of the effect with the metronome. Additionally, a different type of contrast was used. Subsequently, the study by Miller et al. (2024) used a rotating white wand with a tangential velocity of 4 m/s to detect this effect [41]. Future studies might therefore employ more similar devices where individual parameters can be adjusted more easily, such as a rotating disc with a point of varying sizes, allowing all other parameters to be kept constant more straightforwardly to isolate their impact.

Furthermore, Bullough et al.'s study was conducted in a dark-painted room with no other light sources. Future research could explore the impact of contrast between the object and background (for example, by using a lighter wall color) [30,37].

A higher duty cycle generally leads to a reduced perception of the stroboscopic effect. However, in the studies by Bullough et al. (2011), the differences were not statistically significant when testing increases from 10% to 50% duty cycle [24]. Conversely, Wang et al. (2015) identified a significant U-shaped relationship, with a minimum at 30% duty cycle [28]. It is possible that Bullough et al. assumed a linear relationship, which led to no significant difference being observed. Bullough et al. (2016) also investigated the dependency of detection probability at higher duty cycles of 60, 75, and 90% and confirmed significant effects at these levels [30]. Future studies could verify the U-shaped relationship with the duty cycle and the associated minimum. The minimum may shift with different parameter combinations or may not be universally confirmed.

Moreover, the modulation waveform type affects the perceptibility of the stroboscopic effect. In studies by Perz et al. (2015), subjects were more sensitive to a square waveform across all tested frequencies than to a sinusoidal one [27]. The ratio of the two waveforms is nearly constant at $\pi/4$ (approximately 0.79), corresponding to the reciprocal of the amplitude of the fundamental frequency of the square wave (according to de Lange's theory) [27,28]. In addition to square and sinusoidal waveforms, other temporal waveforms exist. Bullough et al. (2016) found significant differences for triangular and trapezoidal patterns besides square wave signals [30]. However, depending on the frequency and visual task, these differences are not universally applicable based on their results. Miller et al. (2024) used 74 TLM waveforms to detect the visibility of the stroboscopic effect [41]. The authors concluded this effect is more visible under rectangular and sinusoidal TLM, higher modulation, and when duty cycles are 10% or 30% and 50%. Future studies could investigate whether there is a mathematical principle for different waveforms and compare theoretical waveforms with practical ones.

Regarding the correlated color temperature, Bullough et al. (2011) found no effect of color temperature (between 2700 K and 4000 K) on the perception of the effect [24]. Since the referenced papers also employ color temperatures within this range, no impact on the results is anticipated (see Table 2). However, these authors also did not recognize the effect of duty cycle, possibly due to their experimental methodology, where participants performed different movements that could only be controlled to a limited extent. Subsequent studies could validate the results across different parameters, more test subjects, and under more reproducible experimental conditions.

Perz et al. (2015) also demonstrated that the effect is less perceivable when parts of the disc are covered, making the visible curve or trajectory appear shorter to the participants [27]. Furthermore, the speed of the moving object affects the perception of the effect. Subjects in the studies by Wang et al. (2015) were more sensitive to the effect at higher stimulus speeds [28].

For a frequency of 100 Hz, a U-shaped relationship with illuminance has been observed, with the minimum occurring between 10 and 100 lx, specifically at 50 lx. When frequencies increase to 200 Hz and 300 Hz, this relationship becomes less discernible. Variations in illuminance appear increasingly irrelevant at higher frequencies. At 800 Hz, no difference is noted as the effect becomes imperceptible to the subjects [28,32]. Future studies could investigate whether there is an interaction effect and test the relationship across a broader range of values. The lowest visibility threshold was identified at 5 lx [32].

In addition, the visual conditions under which temporal light artifacts are observed should be considered. Human vision operates differently under photopic, mesopic and scotopic conditions, which involve different contributions of cone and rod photoreceptors [68,69]. Under low illumination levels approaching mesopic or scotopic vision, reduced visual acuity and increased visual persistence may lead to higher visibility thresholds and a merging of discrete stroboscopic images into blurred motion percepts.

Moreover, peripheral vision may exhibit different sensitivity to temporal modulation compared to focused foveal vision [70,71]. Since rods are absent in the fovea and more prevalent in the periphery, the perceptual characteristics of temporal light artifacts may vary across the visual field and illumination levels.

Most existing studies were conducted under controlled photopic illumination and primarily with foveal fixation, where cone vision and higher spatial resolution dominate, whereas real-world lighting scenarios, such as night driving or street lighting, often involve mesopic or peripheral vision. Since rod vision exhibits lower spatial resolution and longer visual persistence, the visibility thresholds and perceptual characteristics of temporal light artifacts may differ substantially from those measured under standard laboratory condi-

tions. Systematic investigations comparing photopic, mesopic, and peripheral viewing conditions are therefore still lacking.

4.1.2. Influence of Time of Day or Experiment Duration on Participants' Perception Due to Fatigue

Polin et al. (2015) investigated the impact of participants' age and identified a relationship that may suggest an effect of the time of day [29]. In their findings, younger participants showed a lower sensitivity than older ones. However, aside from age, the subjects also varied in terms of the time of day they were tested. Younger participants were predominantly tested between 10:00 and 14:00, a period during which all participants generally perceived the effect less intensely. Additionally, subjects felt more tired or in a worse mood in these time intervals. Therefore, it is plausible that the time of day, through its impact on fatigue and mood, affects the perception of the stroboscopic effect.

Apart from the time of day, the duration of the experiments could affect the fatigue or concentration of the participants. Lee et al. (2018) noted a systematic difference depending on the order of the experiment [23]. The later the sub-experiments occurred for a given participant, the less sensitive they became. Although the participants had the opportunity to take breaks, the unnatural and repetitive visual task revealed a straining effect.

However, the available evidence remains limited and largely context dependent. The observed differences are often based on specific experimental schedules and small sample sizes, making it difficult to determine whether fatigue and time of day effects are statistically robust.

4.1.3. Variations in Participant Sensitivity: Effects of Age, Gender, Visual Characteristics and Health Conditions

Variations in the results of detection probabilities are not only due to different parameters tested, but also attributable to the individual participants themselves. The participant's perception affects the detection probability of the effect [32]. The characteristics and factors contributing to significant individual differences have not yet been clearly identified. Therefore, when selecting participants for studies, their individual characteristics should ideally be balanced.

Veitch et al. (2019) acknowledged using only young people and not including enough sensitive individuals [35]. There is often an assumption that younger people are more sensitive than older ones [35]. Contrary to this belief, Polin et al. stated in their study that older people are more sensitive to the effect [29]. Additionally, they observed that gender and mood also affect the perception of the effect. In their experiments, men could perceive the stroboscopic effect at higher frequencies compared to women. However, the authors also noted that the timing of the experiments could explain differences among the age groups examined and that the results, depending on the methodology of evaluation, may suggest a difference between age and gender or suggest no difference at all [29]. Therefore, further studies are necessary to verify these findings.

Aside from gender and age, a wide range of participant characteristics can be assessed, such as intelligence, attention, or heart rate. Perz et al. (2018) highlighted that the actual interplay of these factors is highly complex and there is a risk of overspecification when deriving plausible metrics [34]. Thus, it raises the question of which individual characteristics are most relevant for understanding the perception of the effect. For instance, one could argue that there are likely fewer applications for LEDs where significant differences between men and women would matter. Conversely, age differences might imply varying requirements in environments like kindergartens or schools compared to senior centers if age-related differences in the perception of the effect are observed.

Perz et al. also highlighted exceptions in medical contexts, such as individuals prone to epileptic seizures [34]. Their findings indicate that threshold functions derived from typical healthy participants should not be assumed universally applicable. While these “standard observer” metrics are useful for general guideline development, they may underestimate the risk for sensitive populations. Consequently, the relevance of the stroboscopic effect in such medical contexts remains uncertain, and future research should explore this issue in collaboration with healthcare professionals.

Differing sensitivities do not necessarily relate solely to variations in detection probability. For example, Veitch et al. (2020) found that overall acceptability ratings were similar between participants with high and low perceptual sensitivity, yet those in the high-sensitivity group reported greater annoyance [37].

Moreover, a cultural effect has not been substantiated in several independent studies [26,28,35]. Consequently, discrepancies in results due to different countries and cultures can be dismissed in these studies.

Overall, the influence of human factors such as age, gender and individual sensitivity appears to be heterogeneous across studies. Some findings suggest age- or gender-related differences, while others report negligible or inconsistent effects, indicating that perceptual variability is likely context dependent. Moreover, when defining safety standards or exposure guidelines, it is important to account for sensitive populations, as metrics derived from healthy participants may not provide adequate protection. Regulatory limits and design guidelines may therefore require additional safety margins or specific recommendations to ensure the safety and comfort of these groups.

4.1.4. Evaluation of the Acceptance of the Stroboscopic Effect

In principle, it is possible to perceive the stroboscopic effect but it is not necessarily considered as disturbing. Bullough et al. showed, for instance, that flicker disturbs subjects more than the stroboscopic effect itself [24]. When focusing on the stroboscopic effect, the authors found no difference in acceptance for different modulation depths at frequencies beyond 1000 Hz, even though subjects can still partially detect differences under these conditions [25].

For frequencies below 1000 Hz, the authors identified similar dependencies on waveform, modulation and duty cycle as in the analysis of perception thresholds [30]. Additionally, Perz et al. compared their findings with those of Bullough et al. In Bullough et al.’s results, the acceptance threshold is systematically lower, by a factor of 10, for the same modulation depth compared to the detection threshold frequency [25,34]. Perz et al. employed different questions and adapted the approach so that the subject could not directly discern the experiment’s objective. Due to their methodology differing from that of Bullough et al., a greater discrepancy between detection and acceptance thresholds was evident.

Veitch et al. further investigated the relationship between the SVM and participants’ acceptance but found no significant correlation [35,37].

Furthermore, Perz et al. emphasized that determining acceptance thresholds is not a straightforward task and varies greatly depending on the task and individual perception. Future research could specify conditions for different acceptance thresholds across various application areas and validate existing findings. Perz et al. also called for analyzing the effect of other parameters like the duration of exposure or the speed of the object under stroboscopic light [32,34].

4.1.5. Consideration of Alternative Experimental Designs

Veitch et al. (2020) emphasized that future studies should consider a broader range of parameter combinations and more diverse participants, as well as employing different geome-

tries, since minor modifications in the experimental setup can impact the outcomes [35,37]. Different contrast types and the use of different devices for the comparison of vertical and horizontal visual tasks make the results insufficiently comparable [37].

4.1.6. Design and Refinement of Evaluation Metrics

The stroboscopic visibility measure developed by Perz et al. has been refined and validated across multiple studies. However, the adequacy of SVM as a sole metric for deriving standards remains in question. If not sufficient, potential alternative metrics that could be evaluated and compared through further research should be identified.

Perz et al. employed a systematic approach to test the transferability of two hypotheses from flicker theory using three experiments. In the methodology experiment, they aimed to determine a method that minimizes variance among participants as much as possible. By employing a contrast function, the SVM was tailored to a standard observer. In typical office settings, where high speeds and low illuminance levels are absent, they established a valid metric indicating the likelihood of perceiving the stroboscopic effect with a single value [27,32,34]. Perz et al. clarified that the SVM applies under specific conditions typical for office environments, such as illumination around 500 lx and speeds of 4 m/s [27]. Therefore, Perz et al. (2018) advocated for further validation of the SVM in darker settings (e.g., street lighting) and with faster-moving objects (in sports or industry for safety around rapidly rotating machinery, for example) [34]. The European Commission adopted the SVM and defined a threshold of 0.4 for undimmed luminaires [72].

Veitch et al. generally confirmed that higher SVM values increase the likelihood of perceiving the effect for both horizontal (rotating disk) and vertical (metronome) tasks. However, they could not validate the definition that a SVM value of 1 corresponds to a 50% detection probability, despite using a setup with similar parameters to Perz et al. Additionally, they suggest the relationship between the SVM and detection probability appears highly nonlinear, with a minor increase in the SVM value above 0.9 leading to a significant increase in detection probability [35,37]. If different researchers cannot replicate findings under similar conditions, transferring specific threshold values to other scenarios might be challenging. Nevertheless, Zhao et al. (2019) confirmed a superficial relationship between the SVM and the cognitive performance of participants in their experiments [36]. Subsequently, the study by Tan et al. (2023) examined the sensitivity of various temporal light modulation metrics to sampling rates [42]. Stroboscopic visibility measure showed stability across sampling rates, while others, such as P_{st}^{LM} , exhibited greater variability.

The SVM impact of changing the geometry, colors or the reflection characteristics of the stimulus remains unexplored [28].

To address the limitations of the SVM, the Lichtpeter proposed the compact flicker degree (CFD) method, suitable for analyzing all three temporal light artifacts. The CFD method accounts for frequency, amplitude, waveform, contrast, and operating mode (dimming), resulting in a single percentage value [73]. Currently, information about this method is primarily found on the Lichtpeter website. This method could be further investigated and scientifically elaborated in future studies.

4.2. Stroboscopic Effect—Field Research

4.2.1. Further Application Scenarios Affected by the Stroboscopic Effect

To explore the influence of the stroboscopic effect across various practical scenarios, it is essential to identify relevant scenarios, determine pertinent parameter sizes and subsequently translate these into practical experiments. The referenced studies involve laboratory experiments in controlled settings, facilitating the analysis of the impact of different parameters. Practical environments, such as offices or workplaces, have been examined in the

studies by Polin et al. (2015) [29], Sekulovski et al. (2020) [38] and Zhao et al. (2018) [33]. Under realistic office conditions, the effect has been observed by Polin et al. (2015) at frequencies up to 700 Hz [29]. Additionally, Zhao et al. (2018) demonstrated that more favorable conditions, which are less likely to trigger the stroboscopic effect, also positively affect the alertness of the participants [33]. However, Sekulovski et al. (2020) did not anticipate an increase in complaints during daily work when participants are exposed to slightly modulated light over extended periods, even though it could still potentially trigger the effect [38].

In other potential applications, the stroboscopic effect can impact nighttime driving when LED headlights or traffic signals exhibit temporal light modulation. Industrial environments with rapidly rotating machinery or conveyor systems illuminated by LEDs are also potential scenarios where the effect may compromise operator safety. Sports lighting, such as stadiums or stage and theatrical lighting, may induce perceptual artifacts due to fast-moving objects under modulated lighting, affecting performance or comfort [31,34].

4.2.2. Impact of Supplementary Light Sources and Natural Daylight on the Perception of the Effect in Practical Environments

The laboratory studies were typically conducted in darkened rooms without windows. However, in real-world settings, additional light sources and windows that allow natural daylight are expected. Therefore, future research could explore the impact of other light sources as well as daylight on the perception of the stroboscopic effect [24].

4.2.3. Expected Short- and Long-Term Effects at Different Severity Levels of the Stroboscopic Effect

Zhao et al. (2018) confirmed that in typical office environments, temporally modulated light, capable of triggering the stroboscopic effect, has short-term physiological impacts on participants [33]. The subjects took part in various activities, such as a writing task and the Anfimov table, which is used to assess mental concentration. Except for pupil size changes, differences in other tested parameters were evident. Both the critical flicker fusion frequency, which serves as a fatigue indicator and brainwave patterns changed, leading to subjects feeling increasingly fatigued and less alert under progressively harsher stimuli.

Thus, low frequencies, especially when combined with high modulation depths, should be avoided [33]. Additionally, a correlation between different SVM levels and cognitive performance has been shown. Higher SVM levels affected environmental awareness, nervousness and attention. However, further research incorporating both psychological and physiological factors is required to provide quantitative recommendations for specific applications [36]. In 2023, Veitch et al. examined the effects of temporal light modulation on visual and cognitive performance [43]. TLM at 100 Hz increased the pupil size and ERP dipole strength, particularly in the right hemisphere, while 500 Hz TLM reduced cognitive interference, suggesting its impact on arousal and brain activity. Subsequently, Kang et al. (2024) concluded that the stroboscopic effect had a greater impact on tasks requiring extensive eye and object movements [44]. The study by Zhao et al. (2024) examined the impact of temporal light modulation on psychological responses [45]. The findings showed that higher SVM levels negatively affected motion perception and work performance. Even if the effect is not directly visible, people were affected by the modulated light. The extent to which this impacts actual work performance remains a question for future studies [40].

Wang et al. (2015) and Polin et al. (2015) also called for investigations into the long-term consequences of the stroboscopic effect [28,29]. Sekulovski et al. (2020) investigated the long-term impacts on individuals in the workplace [38]. However, their research, conducted under relatively mild conditions, failed to provide significant findings regarding the control of

lighting itself. Considering the known short-term effects, future research should aim to either confirm Sekulovski et al.'s results or resolve inconsistencies by providing new data.

While the stroboscopic effect has been widely studied, the phantom array effect shares some similarities but also presents unique challenges. In the next section, we focus on the gaps in research on the phantom array effect.

4.3. Phantom Array Effect—Fundamental Research

4.3.1. Impact of Individual Sensitivity and Participant Characteristics

Generally, there were significant interpersonal differences in the perception of the effect among the individual participants [29]. The varying threshold frequencies across different studies highlight the importance of considering and comparing diverse parameters to understand the conditions under which the effect occurs. The impact of individual visual perception on this effect remains incompletely answered [52].

The studies predominantly used participants with normal, healthy vision. In their research on the impact of saccadic speed, Brown et al. (2020) identified a weak but notable link between the speed of eye movements and discomfort experienced during everyday visual activities. Therefore, an increase in symptoms led to a greater perception of the phantom array effect, even at higher frequencies. Further research is needed to elucidate the relationship between human health and the perception of the effect [52].

Roberts and Wilkins (2013) also conducted a survey involving a participant who utilized colored overlays while reading to alleviate fatigue. This participant perceived the effect at higher frequencies than other participants without problems in the visual system, indicating increased sensitivity possibly due to more sensitive eyes [48].

The sensitivity of participants may depend on many more factors. The effect of various diseases, such as migraine or epilepsy, which are relevant in flicker investigations (see [34]), is typically not considered. However, it is also crucial to investigate the impact on the entire population, including these special groups [74–77]. In 2024, Miller et al. examined the phantom array effect in 55 participants, including 25 with migraines [59]. Migraine sufferers showed higher PAE visibility, greater sensitivity at higher frequencies and increased annoyance, with 64% reporting discomfort post-experiment. LEDs are used in all possible areas of daily life. To reduce risks to these sensitive participants, the analysis of these special cases should be conducted only with medical advice and support during experiments.

4.3.2. Effect of Time of Day

Lee et al. (2018) examined the stroboscopic phantom array effect and proposed that the time of day during which participants were tested could influence the study's outcomes [23]. A practical scenario for the phantom array effect is night driving. However, the fundamental parameters were primarily analyzed during the day, they may not be fully transferable to nocturnal conditions. Therefore, future studies could investigate the effect of time of day on the perception of the phantom array effect.

4.3.3. Key Parameter Influence on the Phantom Array Effect

The perception of the effect is influenced by various parameters. The diverse threshold frequencies across studies underscore the necessity of examining and comparing different parameters to enhance our understanding of the conditions that lead to the effects perception [47,52]. Simply specifying a certain frequency is therefore not sufficient for consistently preventing the effect [47].

Generally, the detectability of the effect decreases with an increase in frequency, a larger duty cycle and a smaller modulation depth [47,49]. Nonetheless, Wang et al. (2017) advocate for more detailed investigations across a broader range of frequencies to derive a sensitivity curve [49]. In a subsequent study, they identify a U-shaped trend where

the median tested frequency (600 Hz compared to 100 Hz and 1200 Hz) most effectively triggered the effect, albeit in an indirect lighting scenario with atypical contrast ratios [51]. Kong et al. (2023) concluded that the phantom array effect exhibits an inverted U-shaped sensitivity profile with respect to temporal frequency [56]. Furthermore, Kang et al. (2023) examined the highest frequency limit of the phantom array effect using an LED light source and the weighted up-down method [58]. The mean threshold frequency for young adults was around 10 kHz, with some participants perceiving the effect above 15 kHz, particularly those with faster eye movements.

Although such thresholds above 15 kHz were primarily observed under optimized laboratory conditions, they indicate that the phantom array effect cannot be categorically excluded at very high frequencies. Given the complexity and variability of real-world lighting environments and individual visual behavior, these findings highlight the need for cautious interpretation when defining regulatory limits, especially to ensure adequate protection of sensitive observers.

When considering the lighting itself, luminance and illuminance play significant roles. While the impact of luminance on the phantom array effect's perception is generally confirmed [47], a broader range of luminance levels might better illustrate the precise relationship. Lee et al.'s experiments included only three luminance levels (25, 100, and 400 cd/m²), leading to the conclusion that threshold frequency increases proportionally with the logarithm of luminance. However, they also noted this relationship may only apply under specific conditions for the tested parameters [50,53]. The interaction with ambient light or the contrast ratio with the environment could be intriguing here [47,53].

The effect of the spectral variation in the light source has been outlined by Kang et al. (2022), demonstrating that the threshold frequency increases for different color perceptions of the spectra in the order green > warm white > red > cool white > blue [55]. Future studies could investigate the perception of the phantom array effect depending on the wavelengths of the used spectrum.

A facet that remains insufficiently investigated within the context of the phantom array effect pertains to the waveform characteristics themselves. Miller et al. (2023) investigated the visibility of the phantom array effect with targeted tasks under 74 TLM waveforms [41]. The authors concluded PAE is more visible under rectangular and sinusoidal TLM, higher modulation, and when duty cycles are 10% or 30% and 50%. While it is presumed that rectangular waveforms might make the phantom array effect more noticeable due to their abrupt transitions compared to sinusoidal patterns [48], this area also requires additional research to further quantify the differences [49].

4.3.4. Comparison of Spatial Configurations

The perceptibility of the phantom array effect generally decreases with a larger stimulus size. Therefore, a small, sharp stimulus triggers the effect more effectively and thus results in higher perception thresholds [47,52]. The effect of angular width is also clearly evident from the test results of Park et al. (2020) [53]. The greater the angular width of the stimulus, the less visible the effect becomes. The perceived beam size and the angular width also correlate with the distance to the test person. If the test person is sitting at a greater distance, the beam size or angular width appears smaller to the subject. It can therefore be assumed that, up to a certain distance, the effect is better perceived when the subject is further away from the light source. The analysis of the distance could be useful for theater lighting, for example, to ensure that even the rearmost rows of seats cannot perceive the effect. When comparing the experimental setups, it is noticeable that either lines or circles are often used as stimuli. Future studies could investigate what influence the shape of different stimuli has on the perceptibility of the effect.

The experiments also differ with regard to a direct or indirect lighting scenario. In a direct scenario, the observer looks at the LED itself during the saccade movements. If, for example, the observer looks at a line during the saccade movements, as in the experiments by Wang et al. (2019), which is illuminated by the LED, this is an indirect lighting scenario [51]. In their experiments, for example, the authors found no effect of illuminance and a U-shaped curve for the frequency dependence (see previous research question). Subjects may not react as sensitively in an indirect scenario. Future research could provide more information here.

Wang et al. (2017) and Roberts and Wilkins (2012) also assumed that different saccade amplitudes of 20° or 40° affect the saccade velocity and thus the perception of the effect [48,49]. The authors could not confirm this either and called for further investigation of the influence of saccade velocity. However, Polin et al. (2015) showed that the cut-off frequency is higher for horizontal saccades than for vertical saccades and attributed this effect to a higher saccade velocity during horizontal eye movements [29]. Kang et al. (2023) investigated the relationship between saccadic eye movement speed and phantom array visibility at two different angles (15° and 30°) and four different directions of saccadic eye movement (right upward, rightward, right downward, downward) [57]. The authors concluded that phantom array visibility increased as eye movement speed increased. Furthermore, the phantom array visibility was higher at a wide viewing angle with fast eye movement speed than at a narrow viewing angle. Future studies could test more amplitudes to confirm the findings for a wider range of values. As eye movements can be very individual, eye trackers, for example, can be used to track and document the movements.

4.3.5. Mixed Stroboscopic—Phantom Array Effect

Lee et al. (2018) also investigated the combined stroboscopic–phantom array effect [23]. This interaction has important implications for the development of evaluation metrics, as existing metrics such as SVM and recently proposed PAE measures are typically derived under conditions involving either object motion or eye movement in isolation. As a result, they may not adequately represent real-world situations in which both mechanisms occur simultaneously. Future models should therefore incorporate relative motion parameters, such as saccadic velocity and light source speed, to improve the prediction accuracy of temporal light artifacts in dynamic applications. Furthermore, the influence of lower motion speeds and higher modulation frequencies on the interaction effect warrants systematic investigation. It would also be valuable to examine whether the effects of established parameters, including light geometry, illumination level and color characteristics, can be generalized to the combined stroboscopic–phantom array condition.

4.3.6. Metric Development for Assessing the Phantom Array Effect

To date, there is no established metric for characterizing the phantom array effect. Similar to the development of the SVM method, more research is necessary in this area. Perz et al. (2019) emphasized that the SVM is not suitable for characterizing the phantom array effect because, despite certain similarities, the processing in the brain takes place in a different way [34]. The authors draw attention to the urgency of a measure for the phantom array effect. The CFD method of Peter Erwin (Lichtpeter) could serve as a possible approach for determining the perceptibility of the phantom array effect. The result is a single value in % where a number of parameters (frequencies up to 20 kHz, waveform, contrast, dimming...) are taken into account [73]. In 2024, Tan et al. (2024) introduced the phantom array visibility measure as the first dedicated metric to quantify the visibility of the phantom array effect [60]. The method involves a Fourier decomposition of the temporal light modulation waveform, where each frequency component is weighted by

an empirically derived log-normal sensitivity function peaking at approximately 695 Hz. The weighted components are then combined using a Minkowski summation with an exponent of 2.1, with PAVM = 1 representing the threshold of perception. Unlike the stroboscopic visibility measure, which targets lower frequency motion artifacts caused by continuous movement, PAVM is designed to model the visibility of PAE due to saccadic eye movements at higher frequencies up to 20 kHz. While SVM shows poor correlation with phantom array visibility, PAVM achieves a high predictive accuracy ($R^2 \approx 0.91$) based on psychophysical data. The authors propose PAVM as a complementary tool to flicker visibility measure (FVM) and SVM for the comprehensive assessment of temporal light artifacts in LED systems.

Despite recent progress in metric development for the PAE, several fundamental challenges prevent the establishment of a universally accepted standard. First, the perceptual mechanism underlying PAE is strongly dependent on saccadic eye movements, which are highly variable across individuals and difficult to control experimentally. Unlike the stroboscopic effect, which is primarily driven by stimulus motion, PAE depends on internally generated oculomotor behavior, introducing substantial inter- and intra-subject variability.

Second, the relevant frequency range extends into the kilohertz domain, where perceptual sensitivity is influenced by complex interactions between retinal persistence, temporal filtering, and luminance adaptation. This makes it difficult to define a single, stable sensitivity function that generalizes across luminance levels, spectral distributions, and viewing conditions.

Third, existing psychophysical datasets remain limited and often collected under highly controlled laboratory conditions with simplified stimuli and restricted eye movement patterns. This restricts the generalizability of derived models such as PAVM and complicates validation under real-world dynamic viewing conditions.

Finally, unlike flicker or stroboscopic perception, PAE involves a combination of spatial and temporal integration during rapid eye movements, meaning that both stimulus geometry and oculomotor dynamics must be incorporated simultaneously. This multidimensional coupling significantly increases model complexity and limits the transferability of simple scalar metrics. These challenges explain why current approaches remain fragmented and why a fully standardized metric for PAE is still lacking.

Knowledge of the influence of the various parameters can be used with more participants to capture not only individual discrete values, but also a wider and more precise range of information. This allows dependencies to be expressed in proper functions, as is the case in more recent studies. All this information can support the development of a reliable metric.

4.4. Phantom Array Effect—Field Research

4.4.1. Relevance of Different Scenarios for the Phantom Array Effect

While controlled laboratory environments are suitable for a better understanding of the influencing factors, the transfer to practice is equally relevant. In practical applications, the phantom array effect is particularly relevant for nighttime driving. Depending on the scenario under consideration, different parameters (lighting levels, speeds, contrast ratios, etc.) may be relevant. To date, only a few studies have taken up research on the phantom array effect in realistic scenarios.

Polin et al. (2015), for example, investigated the perceptibility of the effect for sizes and scenarios that are relevant for automotive lighting situations at night [29]. The authors performed the tests in the laboratory under conditions that were as realistic as possible to evaluate which situations are most likely to trigger the effect. In principle, the findings were transferable to practice, even if the demands on the lighting are somewhat lower, as, for example, the secondary tasks while driving (concentration on the driving itself, the road

and the surrounding traffic) have an effect on the threshold frequency. The phantom array effect could also be interesting, for example, in cinematic applications [52,53], stadium, theater or musical lighting, where the audience quickly looks from one side of the stage to the other side of the stage, which is set in scene by LED light sources.

Wang et al. (2019) examined the detectability of the effect under office conditions in a reading context and concluded that the phantom array effect is not to be expected here under normal office conditions [51]. Nevertheless, the authors add that a rectangular waveform in combination with lower duty cycles and other frequencies could lead to a different result.

4.4.2. Examination of the Effect's Impact on Visibility and User Acceptance in Realistic Scenarios

In contrast to the stroboscopic effect, the separation of perceptibility and acceptance for the phantom array effect may be more difficult to characterize. Vogels and Hernando investigated the effect of frequency, beam size and duty cycle. The test subjects rated on a 5-point Likert scale whether the effect is perceptible and disturbing, perceptible but not disturbing or not perceptible at all.

The authors concluded from the results that the effect is less visible for a larger beam size and is also not perceived as disturbing for a small beam size. Since the acceptance limits are very individual and also depend on specific scenarios, the analysis is not a simple task and can differ significantly even under the same conditions, as Perz et al. showed in a comparison with the results of Bullough et al. for the stroboscopic effect [34]. The authors note that more acceptance limits should also be tested for the phantom array effect. A realistic scenario in which the subjects watch a theater play, drive a car or work under office conditions could be a suitable starting point to make it easier for the subjects to evaluate the acceptability of the effect, if they perceive it.

4.4.3. Health Implications of the Effect, Including Short- and Long-Term Outcomes

The influence of the effect on the observer's health and long-term consequences has not yet been sufficiently investigated. Polin et al. (2015) recommend a combination of subjective and objective (e.g., EEG, eye tracker) measurement methods and also suggested including particularly sensitive people [29]. Brown et al. (2020), for example, found an (albeit weak) correlation between the recognizability of the effect and discomfort during daily visual tasks [52]. In their experiments, a higher discomfort during daily visual tasks led to a more sensitive perception of the phantom array effect at higher frequencies. The study by Miller et al. (2024) concluded migraine sufferers exhibited higher PAE visibility, greater sensitivity to high frequencies, and increased discomfort, with 41% reporting headaches post-experiment [59]. In general, more research is needed to explain the relationship between human health and the perception of the effect [52].

4.5. Summary of Identified Research Gaps

Current research on temporal light artifacts is largely divided into two independent domains: the stroboscopic effect and the phantom array effect. While extensive studies have investigated individual perceptual thresholds and influencing parameters, these investigations remain fragmented across different experimental paradigms, lighting conditions, and evaluation criteria. As a result, there is limited cross-study comparability and a lack of unified interpretation across the broader LED research field.

The identified research gaps suggest that challenges in assessing TLAs primarily arise from inconsistent methodologies, incomplete consideration of LED driver technologies, and limited validation of perceptual metrics. While numerous studies have explored parameter visibility thresholds, the lack of standardized experimental protocols and unified assessment criteria restricts comparability and practical applicability. Furthermore, existing

international standards address only selected aspects of TLA perception and do not fully reflect the diversity of real-world lighting scenarios.

This review addresses these limitations by systematically integrating findings from both stroboscopic and phantom array effect research into a unified analytical framework. By consolidating 40 experimental studies, it enables direct comparison of key influencing factors, including modulation characteristics, observer properties, and experimental methodologies.

The main innovation of this work lies in establishing a structured synthesis that bridges isolated research domains and highlights shared perceptual mechanisms across different temporal light artifacts. In addition, the review critically evaluates existing metrics such as the SVM and the emerging PAVM, identifying their limitations and outlining directions for future standardization.

5. Conclusions

Temporal light artifacts such as the stroboscopic effect and the phantom array effect can occur when LEDs are driven using pulse-width modulation. Figure 13 illustrates a conceptual framework of this work, providing a clearer understanding of the relationships between light source parameters, perceptual thresholds, health impacts and standards.

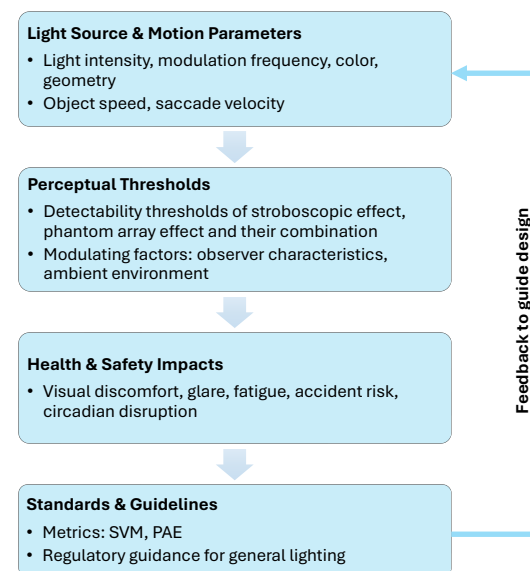


Figure 13. Conceptual framework of this study, illustrating the overall structure and key relationships addressed in the work.

In this work, a systematic review of 40 studies was conducted, including 22 addressing SE and 18 addressing PAE. A key source of inconsistency across the reviewed literature arises from methodological variations between studies, which significantly limit direct comparability of reported thresholds and perceptual functions.

Firstly, differences in experimental setups are substantial. Studies employ either object motion paradigms (e.g., rotating rods or moving targets) or eye movement paradigms (e.g., saccadic tasks or metronome gaze shifts), which directly influence whether the stroboscopic or phantom array mechanism dominates perception. In addition, lighting geometries vary between direct viewing conditions (observer looking at the LED source) and indirect illumination scenarios, where the stimulus is reflected or embedded in the environment. These differences alter contrast ratios, retinal exposure, and effective temporal modulation, making threshold comparisons across studies non-trivial.

Secondly, measurement techniques and psychophysical procedures differ considerably. Some studies rely on forced-choice detection tasks, while others use Likert scale annoy-

ance or visibility ratings. Furthermore, threshold estimation methods vary (e.g., staircase methods, adjustment procedures, or fixed stimulus sampling), which can lead to systematic shifts in reported sensitivity due to response bias or differing decision criteria.

Thirdly, participant samples are highly heterogeneous across studies. Sample sizes are often limited (frequently below 30 participants), with inconsistent inclusion of age groups, gender balance, and visual health status. Most studies focus on young, healthy observers under photopic conditions, whereas real-world applications involve broader populations and mesopic or peripheral viewing conditions.

These methodological inconsistencies collectively contribute to substantial variability in reported thresholds and functional relationships. As a result, differences in findings across studies may not solely reflect perceptual phenomena but also methodological artifacts. This highlights the need for standardized experimental protocols to improve cross-study comparability and the robustness of derived perceptual models.

Based on the literature review, nine key research gaps were identified for each effect, as summarized in Table 6. These effects lead to spatial distortions that become visible during motion or rapid eye movements. Moving objects may appear discontinuous, and individual light sources can be perceived as multiple instances forming a sequence [3]. In contrast to flicker, which has been extensively studied, the stroboscopic and phantom array effects remain insufficiently understood and continue to require focused research [4,5]. These artifacts can be visually disturbing in applications involving dynamic visual tasks such as viewing sports events or driving at night [29,78]. Furthermore, there is evidence suggesting that stroboscopic lighting conditions may negatively affect cognitive performance and increase fatigue [36,40].

Table 6. Summary of the nine key research gaps identified for theSE and the PAE based on the literature review.

Effect Category	Research Category	Research Gap
Stroboscopic Effect	Fundamental research	1. Key parameters of the stroboscopic effect perception 2. Influence of time of day or experiment duration on participants' perception due to fatigue 3. Variations in participant sensitivity: age, gender, visual characteristics and health conditions 4. Evaluation of the acceptance of the stroboscopic effect 5. Consideration of alternative experimental designs 6. Design and refinement of evaluation metrics
	Field research	1. Further application scenarios affected by the stroboscopic effect 2. Impact of supplementary light sources and natural daylight on the perception of the effect in practical environments 3. Expected short- and long-term effects at different severity levels of the stroboscopic effect
Phantom Array Effect	Fundamental research	1. Impact of individual sensitivity and participant characteristics 2. Effect of time of day 3. Key parameter influence on the phantom array effect 4. Comparison of spatial configurations 5. Mixed stroboscopic–phantom array effect 6. Metric development for assessing the phantom array effect
	Field research	1. Relevance of different scenarios for the phantom array effect 2. Examination of the effect's impact on visibility and user acceptance in realistic scenarios 3. Health implications of the effect, including short- and long-term outcomes

For both effects, visibility thresholds cannot be universally defined by frequency alone. Instead, a complex interplay of parameters, including frequency, duty cycle, modulation

depth, waveform shape, illuminance and movement characteristics, determines the visibility of these artifacts. Higher frequencies, larger duty cycles and lower modulation depths generally reduce the visibility [30,47,49], although such relationships may only apply beyond certain thresholds. For example, ref. [51] identified a U-shaped relationship between frequency and phantom array visibility, and between duty cycle and stroboscopic visibility. A similar pattern is suspected for the influence of illuminance on the stroboscopic effect [28], while lower illuminance tends to reduce phantom array sensitivity [51,54]. Additional factors for the phantom array effect include beam size and source brightness, particularly because the light source is within the observer's field of view [47]. The phantom array effect is also triggered by saccadic eye movements, and while a dependency on saccade amplitude or velocity is suspected, only differences between horizontal and vertical saccades have been confirmed [29,49].

In contrast, the stroboscopic effect is typically triggered by the movement of the stimulus rather than eye movement. Here, stimulus speed and trajectory significantly influence perception [27,28]. The waveform used, often sinusoidal or square, is also important, with square waveforms considered a worst-case scenario due to their steep rise and fall times [27]. More research is needed on the impact of waveform shape on phantom array visibility [49]. Regarding chromaticity and color temperature, more is known in relation to the phantom array effect than to the stroboscopic effect [24,55]. Moreover, Differences in experimental design and methodology may account for inconsistencies across studies [35,37]. Factors such as age, gender, physical condition and time of day are also believed to contribute [29].

Among the large number of influencing parameters, two factors emerge as most critical for practical mitigation of visual discomfort in real-world lighting applications: temporal modulation frequency and modulation depth.

Temporal frequency primarily determines whether temporal light artifacts fall within the perceptual sensitivity range of the human visual system. Across both stroboscopic and phantom array effects, increasing frequency consistently reduces perceptibility, with upper thresholds strongly dependent on experimental context and observer characteristics. Therefore, frequency can be considered the primary parameter governing the transition between perceivable and imperceptible temporal modulation.

Modulation depth directly determines the strength of luminance variation within each cycle. A reduction in modulation depth has been consistently shown to reduce both detection probability and perceived annoyance, often independently of waveform shape or spatial configuration, particularly at higher frequencies. This makes modulation depth a highly effective parameter for minimizing visual discomfort in practical LED applications.

While additional factors such as waveform shape, duty cycle, and spatial geometry also contribute to perceptual outcomes, frequency and modulation depth represent the most robust and universally applicable control variables for reducing temporal light artifacts in real-world lighting design.

Despite these growing insights into technical parameters, substantial variability between observers persists. This inter-individual variability is unlikely to be purely methodological and may also be associated with underlying visual and neurophysiological factors that are seldom controlled in existing lighting studies. Accordingly, future studies should more rigorously characterize observer factors that may influence temporal light perception, including visual acuity, contrast sensitivity, migraine history and circadian state. From a broader neuro-visual perspective, measures of visual field sensitivity, electrophysiological responses, and oculomotor behavior (including saccades, pursuits and vestibulo-ocular reflex coordination) could help explain inter-individual differences and strengthen the statistical robustness of visibility models.

As with the stroboscopic effect, there are still unresolved research questions surrounding the phantom array effect. These include further investigation and validation of relevant parameters, as well as the explanation of discrepancies between studies. Open questions also relate to individual sensitivity, potential short- and long-term health consequences and whether medical conditions such as migraines or epilepsy should receive special consideration. Moreover, translating theoretical findings into real-world applications is essential for a better understanding of visibility and user acceptance.

Addressing these research questions requires a controlled and adaptable experimental setup that enables precise adjustment and documentation of all relevant parameters. This allows for reproducible and comparable results. Additionally, the chosen methodology must minimize uncertainty and prevent guessing from participants. Sufficient adaptation time and pre-training can help standardize testing conditions.

The insights gained from this work may help define or refine metrics for different application scenarios. The stroboscopic visibility measure has become increasingly established in recent years [34]. This is reflected not only in its use by independent researchers, but also in policy decisions, such as the adoption of an SVM threshold of 0.4 in 2019 [72]. Despite its robustness, the SVM has limitations. It is primarily applicable at high illuminance levels and does not fully account for dimmed lighting. This suggests the need to either improve the general applicability of SVM or consider alternative models. One such candidate is the CFD approach [73], which, despite its universality, has received little attention so far. CFD may also serve as a useful foundation for modeling the phantom array effect, which still lacks a validated metric.

Once both effects can be reliably characterized by standardized metrics, their visibility can be more easily predicted. This benefits consumers seeking flicker-free lighting, manufacturers striving for quality compliance and policymakers aiming to regulate light sources for public health.

This work is limited in scope. Beyond technical and geometric considerations, biological aspects of the human visual system are likely to play a role in explaining perceptual differences, yet were not covered here. Moreover, a systematic limitation of the reviewed literature is the strong reliance on small participant samples. In many experiments, fewer than 30 participants were included, predominantly young and healthy adults. Such limited and non-representative sampling may introduce participant bias and restrict the generalizability of the findings.

Future research on temporal light artifacts should move from isolated parameter studies toward an integrated and standardized research framework. Based on the findings of this review, several key directions can be identified.

First, there is a strong need for standardized and reproducible experimental frameworks. This includes harmonizing measurement methodologies, defining consistent visibility thresholds, and systematically controlling key parameters such as modulation depth, frequency, waveform, and observer eye movement conditions. Standardization would significantly improve cross-study comparability and enable the development of transferable perceptual models.

Second, future research should focus on the development and validation of unified perceptual metrics for both stroboscopic and phantom array effects. While SVM has achieved partial standardization for stroboscopic perception, the phantom array effect still lacks a robust and widely validated equivalent. Emerging models such as PAVM and CFD should be further tested under diverse real-world conditions, including different luminance levels, spectral compositions, and dynamic viewing scenarios.

Third, more research is required to bridge the gap between laboratory studies and real-world applications. This includes investigating temporal light artifacts under mesopic

and peripheral vision conditions, as well as in realistic environments such as automotive lighting, workplaces, and public spaces. In addition, future models should incorporate inter-individual variability by integrating visual, oculomotor, and neurophysiological factors to improve predictive accuracy.

The research questions proposed here are based on the reviewed literature and also incorporate original reasoning. This work contributes to identifying theoretical knowledge gaps while also emphasizing the practical need for further investigation.

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Abbreviations

The following abbreviations are used in this manuscript:

TLM	Temporal light modulation
LED	Light-emitting diode
TLA	Temporal light artifact
SVM	Stroboscopic visibility measure
PWM	Pulse-width modulation
AC	Alternating current
DC	Direct current
CCT	Correlated color temperature
TCSF	Temporal contrast sensitivity function
EEG	Electroencephalogram
CFF	Critical flicker frequency
ERP	Event-related potential
VAS-F	Visual analogue scale
PANAS	Positive and negative affect schedule
IES	Illuminating engineering society
PAE	Phantom array effect
PAVM	Phantom array visibility measure
CIE	International commission on illumination
2AFC	2-Alternative forced choice
IEC	International electrotechnical commission
TR	Technical report
TN	Technical note
CFD	Compact flicker degree
FVM	Flicker visibility measure

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