

Article

Visibility and Usability of Protective Motorcycle Clothing from the Perspective of Car Drivers

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Abstract

Aiming to improve nighttime safety for motorcycle riders, this study evaluates the visibility and usability of LED and retroreflective-equipped protective motorcycle clothing versus conventional retroreflective gear. Ten male participants with driving experience were selected based on specific criteria, including normal or corrected visual acuity. Utilizing a simulated driving environment with a 75-inch screen and electric bicycles, the study employed an eye tracker to define recognition distances. It was found that LED and retroreflective-equipped clothing significantly increased the recognition distance in various nighttime scenarios, with the experimental group's gear being visible from substantially further away than the control group's gear. Additionally, subjective assessments showed that the LED gear scored higher in visibility and overall satisfaction, though no significant differences in wearability and activity performance were noted between the two groups. These results indicate that LED clothing could enhance rider safety at night, emphasizing the importance of such innovations for safety gear. Despite its focus on SUV drivers and specific conditions, the study provides foundational data for the development of effective protective motorcycle clothing, suggesting future research should include a broader array of vehicle types and environmental conditions.

Keywords: motorcycle safety; LED clothing; visibility; recognition distance; nighttime riding



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1. Introduction

The COVID-19 pandemic had a profound impact on global economies and societies [1]. Social distancing and self-isolation measures have forced many brick-and-mortar stores to close or limit their hours of operation, which, in turn, has led to a surge in demand for online shopping and delivery services [2]. The rapid increase in motorcycle transportation in developing Asian countries can be attributed to several factors [3]. Motorcycles offer an affordable and flexible means of transport, especially in urban areas where traffic congestion

and narrow streets make larger vehicles less practical. Economically, motorcycles play a vital role by providing livelihood opportunities, such as delivery services and motorcycle taxis [4]. Motorcycles are not only utilitarian vehicles, but also play a significant role in leisure, sports, and travel, forming a vibrant market [5].

As the number of motorcycle accidents has been on the rise, concerns about road safety are increasing [6]. Motorcycles, while offering flexibility and convenience, expose riders to greater risks compared to car drivers. Without the protective enclosure that cars provide, motorcyclists are more vulnerable to serious injuries in the event of a crash [7]. Furthermore, nighttime riding has been identified as significantly increasing the likelihood of various types of accidents, substantially raising the risk not only for riders themselves but also for pedestrians and car drivers [8–10]. Against this backdrop, there has been a growing body of research aimed at enhancing the safety of motorcycle riders and reducing traffic accidents. One key approach to improving rider safety is increasing visibility, enabling other vehicle drivers and pedestrians to easily identify riders, thus contributing to accident prevention [11–13]. Also, development in protective motorcycle clothing is garnering significant interest, with ongoing research steadily progressing to enhance the safety and functionality of gear for riders in diverse conditions [14].

Kwan and Mapstone [8] systematically reviewed randomized controlled trials on visibility aids for pedestrians and cyclists, indicating their effectiveness in preventing accidents by enhancing visibility to other road users, which is crucial for safety interventions. Furthermore, de Rome [15] indicates that while protective motorcycle clothing reduces the risk of injury, it may impair rider safety in heat due to thermal strain. The study measured the heart rate, core and skin temperature, and reaction times of motorcyclists in simulated hot conditions, showing increased core temperatures, heart rates, and reaction times, with negative impacts on mood and alertness, which suggests that current protective motorcycle clothing may compromise cognitive and psychophysical function in heat, highlighting the need for more thermally efficient gear to maintain rider performance and safety. Porchia et al. [16] stated that the introduction of graduated driver licensing and interventions aimed at enhancing the visibility of pedestrians and cyclists constitute effective methods for reducing traffic accidents. Basar and Razik [17] demonstrated that the Smart Motorcycle Safety Vest (SMS-V) with Light Emitting Diodes (LEDs) and Radio Frequency (RF) circuitry significantly improves motorcyclist visibility at night to reduce accidents in Malaysia. Wu et al. [18] examined the effectiveness of protective clothing for motorized two-wheel riders using injury data and a postal survey. They found that protective gear, especially gloves and jackets, significantly reduces the risk of soft tissue injuries but is less effective against fractures, except for boots, which lowered ankle and foot fracture risks. In addition, de Rome et al. [19] found that protective motorcycle clothing significantly reduces hospital stays and pain post-crash, with better recovery outcomes and return to work rates, especially for fully protected riders, highlighting its importance for rider safety and well-being in Australia.

While previous research has focused predominantly on the safety features related to protective motorcycle clothing, studies on usability as perceived by riders have not been fully explored. Consequently, this study aimed to measure the distance at which a driver can visually detect a rider wearing protective motorcycle clothing in a road environment (visibility) and to examine the rider's perception of usability. Before the comprehensive consideration of the variables affecting the experiment results, this study provides an exploratory investigation as an initial phase and suggests a framework that can be used for subsequent research.

2. Materials and Methods

2.1. Materials

This study conducted a comparative analysis by setting protective motorcycle clothing that combines retroreflective materials with LED lighting as the experimental group, and conventional protective motorcycle clothing with only retroreflective materials as the control group.

Both conditions were fabricated based on the same commercial motorcycle safety vest product, with silver retroreflective strips applied at identical locations and areas on the shoulders, arms, chest, and back (Figure 1). The control group's protective motorcycle clothing consisted of silver retroreflective strips and fluorescent yellow retroreflective materials, relying on passive reflection of external light sources (vehicle headlamps) for visibility.



Figure 1. Illustration of protective motorcycle clothing used in the experimental group (a) and control group (b). The experimental group was designed to combine LED lights with retroreflective materials, while the control group relied only on retroreflective materials to reflect external light. The red circles indicate the locations where the retroreflective materials were applied.

The experimental group retained the same base vest but removed the fluorescent yellow retroreflective materials and attached LED lights in the same areas. The LEDs were configured in an alternating red–blue flashing pattern, designed to provide visual signals similar to emergency vehicle lighting, thereby offering active visibility independent of external light sources. The silver retroreflective strips were maintained identically in the experimental group, ensuring that the only difference between the two conditions was the visibility mechanism (active LED illumination vs. passive fluorescent retroreflection).

2.2. Participants

Ethics approval for this study was granted by the Korea Institute of Industrial Technology (KITECH) Institutional Review Board, Republic of Korea (Register Number: KITECH IRB A-2022-010). In this study, a total of ten male subjects with a minimum of two years of driving experience each in automobiles and motorcycles were recruited. The criteria for

participation were as follows. Subjects who would have difficulty confirming the visibility of the target items during the experimental process, such as those with color blindness, were excluded. Among the volunteers, only those who were confirmed to have the ability to distinguish colors and who had normal or corrected visual acuity of 1.0 or higher were selected as subjects for the experiment. This study was conducted ethically in compliance with the Declaration of Helsinki, and written informed consent was obtained after thoroughly explaining the purpose and details of the experiment to the participants. Table 1 presents the aggregate age and driving experience of the participants. The mean age is reported as 34.5 years with a standard deviation of 5.9 years. The mean driving experience for cars is 8.5 years, with a standard deviation of 4.0 years, while the mean motorcycle driving experience is noted as 6.4 years, with a standard deviation of 4.9 years. The mean annual driving distance for the subjects' cars or motorcycles was 2859.4 km, with a standard deviation of ± 5.2 km.

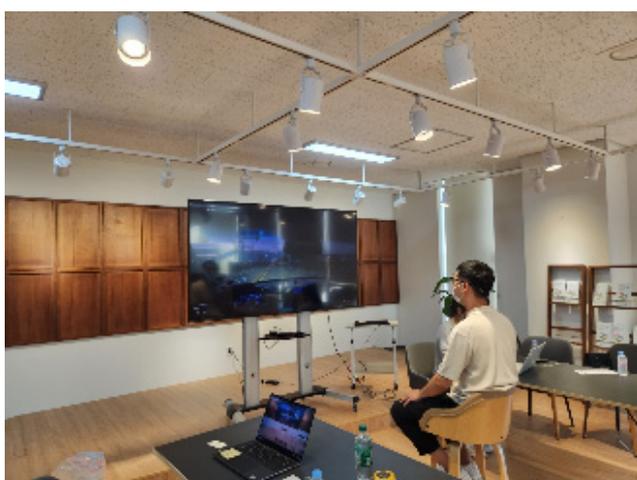
Table 1. Participants' age, vehicle, and motorcycle driving experience.

Category (N = 10)	Age (Years)	Car (Years)	Motorcycle (Years)	Distance (km/Year)
Mean (\pm Standard Deviation)	34.5 (± 5.9)	8.5 (± 4.0)	6.4 (± 4.9)	2859.4 (± 5.2)

A rider's safety suit utilizing LED lights combined with retroreflective materials, which self-illuminate, was designated as the target item for the experiment. Its visibility and usability were compared against a control item, a reflective safety suit illuminated by external light sources.

2.3. Experimental Environment and Equipment

This study set up a 75-inch screen as an experimental environment for measuring recognition distance so that the research subjects could immerse themselves in the perspective of a vehicle driver while watching a recorded video. This study also arranged an experimental environment for usability evaluation that allows for the placement of electric bicycles, which have similar riding and propulsion methods to motorcycles, and to conduct surveys (Figure 2).



(a) Environment for measuring perception distance

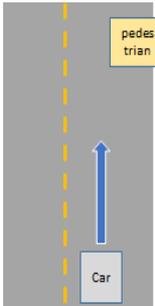
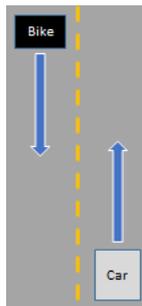


(b) Environment for evaluation of usability

Figure 2. For measuring recognition distance, a 75-inch large screen was installed to allow research subjects to immerse themselves in the perspective of a vehicle driver while watching a recorded video (a). For the usability assessment, the experimental environment was arranged to enable the arrangement of electric bicycles, similar in driving and propulsion to motorcycles, and to conduct surveys (b).

The shooting scenarios for this study were divided into three types, as shown in Table 2: a scenario where a vehicle and a motorcycle are approaching each other, a scenario where the vehicle is following the motorcycle, and a scenario where a vehicle is passing a pedestrian standing by the roadside. The speed of the vehicle was 50 km/h, 30 km/h, and 50 km/h, respectively, while the speed of the motorcycle and pedestrian was 0 km/h. The filming times for this study were scheduled for 30 min after sunset and 2 h after sunset, and both the experimental and control groups were filmed accordingly.

Table 2. Scenario for video recording.

Dept	Scenario											
	(1) Pedestrian				(2) Follower				(3) Face-to-Face			
Three scenarios												
Start point for filming	30 min after sunset		2 h after sunset		30 min after sunset		2 h after sunset		30 min after sunset		2 h after sunset	
Item 1: Experimental 2: Control	1	2	1	2	1	2	1	2	1	2	1	2
Speed	Car: 50 km/h Pedestrian: 0 km/h				Car: 30 km/h Bike: 0 km/h				Car: 50 km/h Bike: 0 km/h			

The experimental vehicle was a 2010 Hyundai Veracruz equipped with factory-installed HID (High-Intensity Discharge) headlamps. The low beam specification used HID D1S bulbs (35 W, 4300 K color temperature), manufactured by Hyundai Motor Company (Seoul, Republic of Korea). All experiments were conducted with low beams only to replicate typical nighttime driving conditions. The horizontal and vertical angles of the headlamps were maintained in their factory settings without adjustment, and no additional luminance control or post-processing was applied to ensure ecological validity of the actual road environment.

All video recordings were conducted on public roads with standard street lighting installed at 40 m intervals. During both time conditions (30 min and 2 h after sunset), street lighting was operational. The 30 min condition featured a mixture of residual natural light and street lighting, while the 2 h condition represented complete nighttime with only street lighting as the ambient illumination source. This repeated filming approach maintained environmental consistency across conditions.

This study evaluated perceived conspicuity based on participants’ recognition levels rather than absolute luminance measurements. LED lighting maintained consistent luminance regardless of vehicle headlamp presence, creating high contrast in nighttime environments. In contrast, retroreflective strips reflected light only when illuminated by headlamps at certain angles and distances, resulting in contrast that varied with environmental lighting conditions.

As shown in Table 3, the camera used for filming the experimental videos in this study was a GoPro 9, which was set up on a headrest mount to avoid obstructing the driver’s view and to approximate the driver’s perspective. A recreational vehicle was used as the vehicle, and a black motorcycle with an F-type body was used. The headlights and taillights

of both the vehicle and motorcycle were controlled because they could affect the visibility of the target and comparison items. The vehicle and motorcycle used for filming were each equipped with a 4Guard GPS device from IoTPLEX (Busan, Republic of Korea), receiving latitude and longitude information, real-time data, and speed every two seconds. For the vehicle, the speed was regulated using cruise mode and by monitoring the GPS device.

Table 3. Equipment used in the experiment.

Experimental Equipment	Brand	Model
Recording camera	GoPro	GoPro9
Eye Tracker	Tobii	Pro Glasses 2
GPS	IoTplex	4Guard GPS

The recorded videos were displayed on the 75-inch screen without post-processing or brightness adjustments. During video playback, the laboratory illumination was maintained below 5 lux to replicate the visual adaptation state similar to nighttime driving inside an actual vehicle. Screen brightness and contrast were set to display standard values, and no image correction features were applied. This set up ensured that participants experienced authentic road lighting conditions, including streetlights, vehicle headlamps, and ambient darkness.

2.4. Procedure

Before conducting the evaluation, the research participants were informed about the purpose of the study and the precautions to be taken. In addition, a preliminary survey on their driving experience with automobiles and motorcycles, as well as any physical limitations, was conducted to determine their eligibility to participate in the final assessment. Those who were selected were guided to the evaluation site for measuring recognition distance, where they were fitted with an eye tracker and underwent calibration. They were provided with sufficient practice time to become familiar with the tasks and the use of the eye tracker. To eliminate learning effects, the prepared participants were shown 12 randomly played recorded videos to participate in the experiment. Moreover, the study director monitored the participants' visual data in real-time according to the experimental design to ensure there were no errors in the eye tracking.

Furthermore, recognition distance was defined as the distance between the vehicle driver and the motorcycle rider when the driver first recognized the rider. After completing the recognition distance measurement and verifying that there were no errors in the eye-tracking data, the participants were guided to the experimental environment with electric bicycles for the evaluation of visibility and usability. The subjects were given enough time to experience the usability of protective motorcycle clothing for both the experimental and control groups. Subsequently, the researchers added tasks such as making left and right turns, mounting and dismounting, and actions like reaching into a pocket or stretching an arm, assuming the participants were riding a motorcycle as presented in prior studies. After performing these tasks, the subjects evaluated the perceived visibility and usability.

A 7-point Likert scale was used to assess subjective visibility and usability satisfaction, ranging from 1 (Very Poor/Very Dissatisfied) to 7 (Very Good/Very Satisfied), with 4 representing a neutral evaluation.

2.5. Data Analysis

For the assessment of the objective measure of relative distance, this study utilized an eye tracker to measure the time from the start of the video to the point where the motorcycle rider or pedestrian was identified. The latitude and longitude values acquired

during filming were used to calculate the measured distance using the Haversine Formula, as shown in Equation (1), which is an equation for determining the shortest distance between two points [20]. Based on this formula, the study calculated the total distance using the latitude and longitude values from the start of the video and those of the stationary motorcycle or pedestrian.

$$d = 2r \arcsin \left(\sqrt{\text{hav}(\varnothing_2 - \varnothing_1) + \cos(\varnothing_1)\cos(\varnothing_2)\text{hav}(\lambda_2 - \lambda_1)} \right) \tag{1}$$

Furthermore, this study calculated the distance to identification by substituting the speed according to the scenario into the time obtained from the start of the video to the point of motorcycle or pedestrian identification. Subsequently, the distance obtained from the total distance minus the distance calculated from the start of the video to the pedestrian identification point provided the distance at which the vehicle driver identified the motorcycle or pedestrian. Table 4 presents the data segmentation areas for measuring recognition distance.

Table 4. Data segmentation for measuring recognition distance.

Category	Data
Recording the Nth Scenario	Real time
	Latitude Data at 2-Second Intervals
	Longitude Data at 2-Second Intervals
	Speed Data at 2-Second Intervals
Viewing the Nth Scenario Video	Latitude Data at the Start of the Video
	Longitude Data at the Start of the Video
	Time Elapsed from the Start of the Video to the Identification of Bicycles/Pedestrians
	Latitude Data of Bicycles/Pedestrians
	Longitude Data of Bicycles/Pedestrians

For subjective evaluation data, paired *t*-tests were performed to examine differences between experimental and control groups. Although Likert scale data are inherently ordinal, there is empirical evidence that scales with five or more points can be treated as interval scales. Based on the previous studies [21,22], it was confirmed that 7-point scales are valid for calculating means and standard deviations, and that parametric tests are practically robust for such data. The analysis calculated means, standard deviations, *t*-values, and *p*-values, with the significance level set at 0.05.

3. Results

3.1. Result of Measurement on Recognition Distance

Prior to conducting parametric statistical tests, data normality was assessed using the Shapiro–Wilk test. For recognition distance data, paired differences between experimental and control groups (experimental minus control) were tested for normality across all scenarios and time conditions. Results indicated that all recognition distance differences followed a normal distribution (Table 5). All Shapiro–Wilk test *p*-values exceeded 0.05, confirming that the normality assumption for paired *t*-tests was satisfied across all conditions.

The measurement of recognition distance for the target items was based on 12 videos, from which the distance was calculated using the time at which motorcycle riders or pedestrians were identified. In all scenarios, participants recognized the experimental group’s motorcycle riders from a farther distance compared to the control group, and this

was statistically significant ($p < 0.001$). For the pedestrian scenario, 30 min after sunset, the experimental group was observed recognizing individuals from about 150.9 m farther away than the control group. In the following scenario, the experimental group recognized the subjects from approximately 131.9 m farther away. Lastly, in the face-to-face scenario, the experimental group was noted to recognize individuals from around 211.8 m farther away than the control group (Table 6).

Table 5. Shapiro–Wilk normality test results for recognition distance differences.

Category	Scenario	W-Statistic	p-Value
Recording the Nth Scenario	(1) Pedestrian	0.944	0.603
	(2) Follower	0.870	0.099
	(3) Face-to-face	0.930	0.443
Viewing the Nth Scenario Video	(1) Pedestrian	0.948	0.639
	(2) Follower	0.927	0.422
	(3) Face-to-face	0.960	0.791

Table 6. Results of the paired *t*-test for recognition distance (30 min after sunset).

Scenario	Experimental	Control	<i>t</i>	p-Value
(1) Pedestrian	229.7 (±2.8)	78.8 (±6.5)	9.495	<0.001 ***
(2) Follower	198.8 (±6.3)	66.9 (±9.7)	12.358	<0.001 ***
(3) Face-to-face	276.3 (±8.4)	64.5 (±7.3)	14.042	<0.001 ***

$p < 0.001$ ***.

Also, two hours after sunset, in the pedestrian scenario, it was found that the experimental group could recognize subjects from about 190.8 m away, which is farther than the control group. In the following scenario, the experimental group was able to recognize subjects from approximately 245.2 m away, which is farther than the comparison target, and in the head-on scenario, the experimental group recognized subjects from about 243.2 m away, further than the control group (Table 7).

Table 7. Results of the paired *t*-test for recognition distance (Two hours after sunset).

Scenario	Experimental	Control	<i>t</i>	p-Value
(1) Pedestrian	312.8 (±16.5)	122.0 (±9.6)	20.220	<0.001 ***
(2) Follower	385.2 (±7.3)	140.0 (±17.4)	10.878	<0.001 ***
(3) Face-to-face	293.3 (±12.8)	50.1 (±10.3)	18.089	<0.001 ***

$p < 0.001$ ***.

3.2. Evaluation of Subjective Visibility

Table 8 and Figure 3 show the results of the evaluation of the visibility in the two groups. The experimental group scored higher in terms of visibility, location appropriateness, and color appropriateness. It was confirmed that there were statistically significant differences in all categories ($p < 0.001$).

Table 8. Results of the paired *t*-test for the visibility evaluation.

Variables	Experimental	Control	<i>t</i> -Value	p-Value
Visibility	6.7 (±0.1)	2.5 (±0.3)	11.225	<0.001 ***
Location	6.6 (±0.2)	3.0 (±0.4)	9.000	<0.001 ***
Color	5.0 (±0.5)	3.0 (±0.3)	3.162	<0.001 ***

$p < 0.001$ ***.

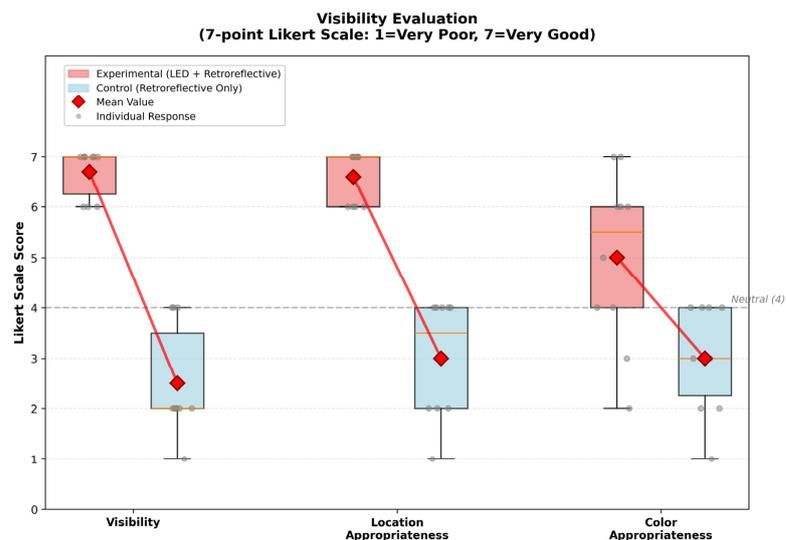


Figure 3. Visibility evaluation.

3.3. Evaluation of Usability

3.3.1. Wearability

In an evaluation of protective motorcycle clothing wearability, a paired *t*-test analysis revealed no significant differences between the experimental and control groups (Table 9 and Figure 4). The assessment measured variables such as weight, size, and ease of dressing and undressing. The findings suggest that the experimental design’s innovations in wearability did not compromise user comfort or function when compared to the control group.

Table 9. Results of the paired *t*-test for wearability evaluation.

Variables	Experimental	Control	<i>t</i> -Value	<i>p</i> -Value
Weight	5.0	4.3	0.817	0.425
Size	5.0	4.8	0.287	0.777
Dressing	5.1	4.4	0.553	0.587
Undressing	4.9	4.5	0.323	0.751
Wearability	5.3	4.5	0.427	0.675

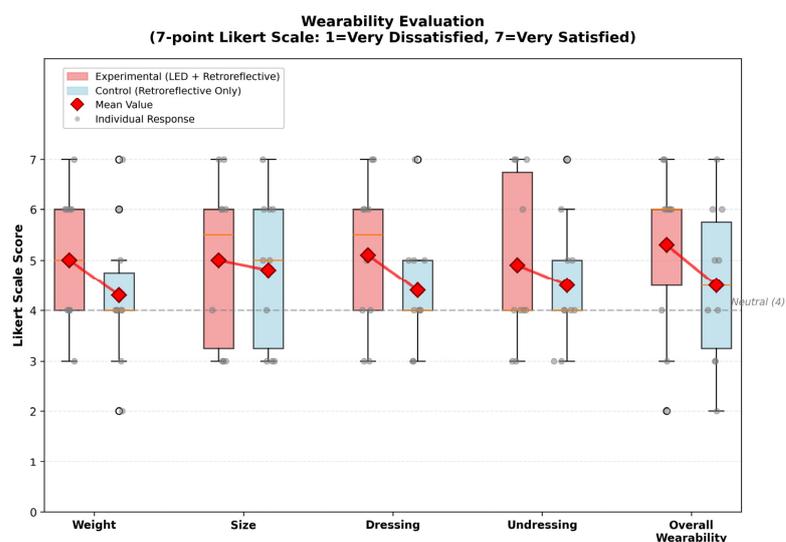


Figure 4. Wearability evaluation.

3.3.2. Activity

Table 10 and Figure 5 show the results from a paired *t*-test assessing the activity performance of protective motorcycle clothing. The variables used in a paired *t*-test were availability, adaptability, and activity. Availability is the extent to which overall body movement was facilitated while wearing. Adaptability is the capacity of protective clothes to be naturally aligned with the body’s movements during specific posture changes (e.g., raising arms, stretching arms, bending the upper body, and bending the arms). Finally, activity is the degree to which the participant’s activity level was satisfactory during continuous or complex physical movements. However, there were no statistically significant differences between the experimental and control groups in all items ($p > 0.05$).

Table 10. Results of the paired *t*-test for activity evaluation.

Variables	Experimental	Control	<i>t</i> -Value	<i>p</i> -Value
Availability	5.3	4.8	0.502	0.622
Adaptability (Raising arms)	4.9	4.2	0.563	0.580
Adaptability (Stretching arms)	5.2	5.0	0.338	0.740
Adaptability (Bending the upper body)	5.6	4.7	0.662	0.517
Adaptability (Bending the arms)	5.7	5.3	0.399	0.695
Activity	5.6	5.0	0.744	0.466

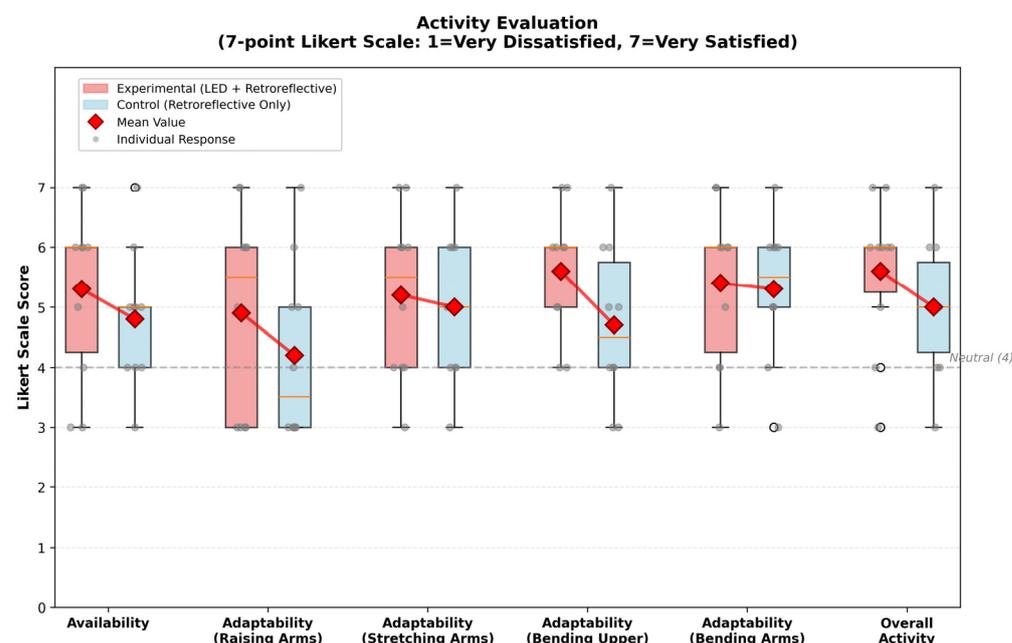


Figure 5. Activity evaluation.

3.3.3. Satisfaction

Table 11 and Figure 6 present a comparative analysis of design preferences and overall satisfaction for protective motorcycle clothing. There was no significant difference in design preference between the two groups, but a statistically significant difference in overall satisfaction was observed between the two ($p < 0.05$).

Table 11. Results of the paired *t*-test for satisfaction evaluation.

Variables	Target	Control	<i>t</i> -Value	<i>p</i> -Value
Design	4.8	4.4	0.586	0.565
Satisfaction	5.7	4.1	2.495	0.023 *

p < 0.05 *.

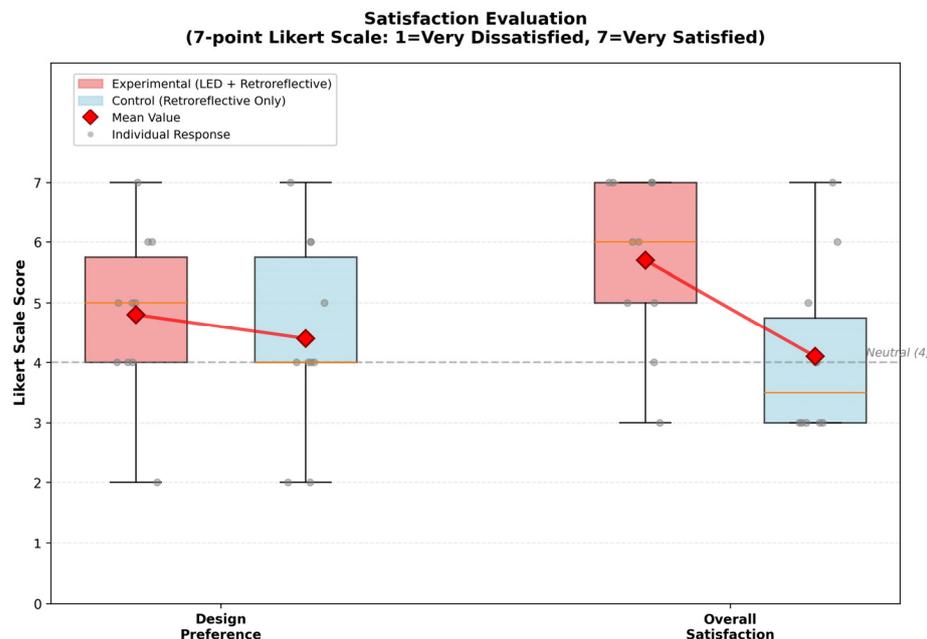


Figure 6. Satisfaction evaluation.

4. Discussion

This study aimed to ensure the safety of motorcycle riders on nighttime roads and to reduce traffic accidents related to them by examining the recognition distance of SUV drivers when wearing newly developed self-illuminating LED safety clothing with retroreflective materials. It also evaluated the overall user experience and subjective visibility. The study compared the effectiveness of the recognition distance and visibility of the light-emitting area, location appropriateness, color appropriateness, wearability, mobility, design preference, and overall satisfaction between the experimental and control groups. In the discussion of the results, it is imperative to contextualize these findings within the broader corpus of safety gear research, which highlights the paramount importance of visibility in preventing road accidents involving motorcyclists.

Our findings show that LED and retroreflective-equipped clothing substantially increased recognition distance in various nighttime scenarios, aligning with Basar and Razik’s [17] advocacy for enhanced visibility as a key safety intervention. This observed increase in visibility can be interpreted as an advancement over traditional retroreflective materials, which, as Wu et al. [18] suggest, offer protection but may not necessarily optimize detection by other road users, especially under limited light conditions.

Furthermore, the recognition distance measured in this study transcends a mere metric of visual detectability and represents a critical safety indicator directly linked to collision avoidance in actual traffic environments. According to the American Association of State Highway and Transportation Officials (AASHTO), which recommends a perception-reaction time of 2.5 s and a deceleration rate of 3.4 m/s² under dry pavement conditions, the total stopping distance is approximately 46 m at 40 km/h and 64 m at 50 km/h [23]. This implies that drivers require advanced recognition of pedestrians or motorcyclists at least equal to or exceeding these stopping distances to complete braking maneuvers

safely. In this study, LED-illuminated protective clothing provided a minimum recognition distance of 198.8 m, which substantially exceeds the required stopping distances. This extended recognition distance enables drivers to detect motorcyclists well in advance of the critical braking zone, thereby significantly enhancing the potential for collision avoidance in real-world traffic scenarios. In addition, this finding serves further robust support for the importance of recognition distances compared to stopping distances, as evidenced by the seminal study of Olsen [24] to the recent review by Samson [25].

Notably, the absence of significant differences in wearability and activity performance between the two groups addresses a critical concern highlighted by de Rome [15], who warns against the impairment of rider safety due to the thermogenic distress caused by protective clothing. By demonstrating comparable wearability, the LED and retroreflective-equipped clothing may offer a dual advantage of heightened visibility without the trade-off in comfort or increased risk of heat strain, thus presenting a more holistic approach to rider safety.

The subjective assessments indicating a higher score for LED gear in terms of visibility and overall satisfaction can be seen as a direct response to the gap identified by Kwan and Mapstone [8], where safety interventions often overlook the usability aspect from the rider's perspective. This subjective satisfaction might translate into increased usage compliance, thereby augmenting safety outcomes, a hypothesis that could be explored in future longitudinal studies examining actual road usage patterns and accident rates. In light of the findings presented by de Rome et al. [19], which advocate for the importance of protective clothing in reducing hospital stays and improving post-crash recovery, the enhanced visibility offered by LED and retroreflective materials may further contribute to these positive outcomes by potentially reducing the incidence of crashes in the first place. The lack of significant differences in the design preference between the two groups indicates that aesthetic factors may not be a primary determinant of safety gear selection for riders. This is a salient point, given that designers and manufacturers must balance aesthetic appeal with functional safety features.

While this study demonstrates the effectiveness of LED-illuminated protective clothing in enhancing nighttime visibility, certain factors warrant further investigation through future research. First, the impact of diverse vehicle headlamp light distributions on the visibility of protective clothing represents an important consideration. In this study, experiments were conducted using factory-standard HID headlamps (35 W, 4300 K) configured in low beam mode, which represents typical nighttime urban driving conditions. However, recent vehicles increasingly incorporate various lighting technologies such as matrix LED systems and adaptive headlamps, and these lighting characteristics may influence the relative effectiveness of LED-illuminated protective clothing and retroreflective materials. Therefore, future research should systematically compare and analyze the effects of different headlamp types and beam distribution characteristics on protective clothing visibility.

Notably, one of the primary advantages of LED-illuminated protective clothing is its reduced dependence on external lighting. While retroreflective materials require direct illumination from vehicle headlamps at specific angles and distances, LED lighting can maintain consistent brightness autonomously, potentially providing stable visibility regardless of vehicle lighting characteristics or ambient illumination levels. This characteristic may contribute to enhancing the detectability of protective clothing across various vehicle and lighting environments, suggesting that LED illumination may partially offset the influence of headlamp light distribution. However, this hypothesis requires empirical examination through experimental comparisons across diverse vehicle lighting systems.

Furthermore, the potential visual effects of LED-illuminated protective clothing on drivers should be carefully evaluated. Although no explicit reports of glare or visual

disturbance were identified from participants in this study, the LED lighting employed included red–blue flashing patterns that could potentially be perceived similarly to emergency vehicle lighting under certain circumstances. While these visual characteristics may provide positive attention-directing effects for drivers, they also present the possibility of inducing unexpected perceptual confusion in traffic-congested situations or complex visual environments. Therefore, future research should systematically analyze the effects of LED lighting flash frequency, color combinations, and brightness levels on driver visual comfort, attention concentration, and misidentification potential, and optimization strategies considering the balance between visual conspicuity and visual comfort should be pursued in parallel.

To this end, this study offers substantial evidence supporting the implementation of LED self-illuminating materials combined with retroreflective elements in protective motorcycle clothing as a means of enhancing nighttime rider safety. While it builds on previous research underscoring the critical role of visibility in safety gear, it also provides new insights into the potential benefits of LED and retroreflective clothing in terms of recognition distance and subjective rider satisfaction. It suggests a promising direction for future innovations in motorcycle safety gear, emphasizing the need for further research incorporating diverse driving scenarios and the impact of these innovations on actual road safety statistics.

5. Limitations and Future Research

This study presents a critical step forward in enhancing motorcyclist safety through the use of protective motorcycle clothing that combines LED self-illuminating and retroreflective materials. However, several limitations are inherent in the study's design and scope, which must be addressed to fully understand the implications and practical applications of the findings.

Firstly, this study was conducted as an exploratory investigation to examine the relative visibility differences between LED lighting and retroreflective materials. The study involved ten male participants with driving experience and employed a within-subjects design to control for inter-individual variability. Statistical significance at the $p < 0.001$ level was achieved across all scenarios, thereby providing reliable initial evidence for the relative effects of LED lighting. Previous studies with similar objectives and procedures have also utilized sample sizes of around 10 participants [26,27]. Nevertheless, the sample size and demographic homogeneity are recognized as factors that constrain the generalizability of the findings. Additional validation is needed to apply these results to the broader population of motorcyclists, which encompasses diverse age groups, genders, and experience levels. In particular, reflecting the varied capabilities and responses of all motorcyclists is critical in assessing the true effectiveness of safety interventions.

Secondly, this study utilized a simulated driving environment to systematically control major external variables during the initial evaluation stage. By controlling factors such as lighting, background contrast, and speed in a laboratory setting, this study focused on identifying the pure effect differences between LED lighting and retroreflective materials. Simulation-based evaluation is a widely recognized methodology in visibility research and offers the advantage of avoiding the safety and ethical considerations associated with measuring recognition distance in actual driving environments. Previous research has also adopted the approach of first validating relative effects in controlled environments during initial stages. At the same time, it is acknowledged that the simulated environment does not fully replicate the multifaceted nature of real-world driving scenarios. Factors such as weather conditions, varying levels of darkness, and the presence of other roadway illumination sources (e.g., streetlights, oncoming headlights) can significantly affect

visibility and recognition distances. This study focuses on deriving relative recognition distance differences rather than absolute field effects, and the applicability across various driving environments, including the unpredictability and variability inherent in actual road situations, can be validated in subsequent field studies.

Thirdly, this study examined the effectiveness of LED and retroreflective clothing under specific conditions, namely, nighttime and interactions with SUV drivers. This was based on practical considerations that nighttime visibility issues are a major risk factor for motorcycle accidents and that SUVs constitute a significant proportion of vehicles on domestic roads. Simultaneously, this specificity of conditions acts as a factor limiting the scope of application of the results. Daytime visibility, interactions with different vehicle types, and various levels of urban and rural driving environments are conditions under which the effectiveness of LED and retroreflective clothing should be further evaluated.

Fourthly, the experimental design of this study focused primarily on examining relative effect differences between lighting methods. Accordingly, LED parameters such as luminance, flicker frequency, and color were maintained under fixed conditions. In safety equipment research, the initial stage typically concentrates on establishing basic effectiveness, with detailed parameter optimization being a standard approach for subsequent stages. Systematic analysis of how LED parameters affect recognition performance will be a primary objective of follow-up research planned based on the findings of this study. Additionally, because this study utilized video-based scenarios, behavioral response indicators such as reaction time and braking distance were not included in the measurement scope. These variables require dynamic driving environments and precision measurement equipment and can be validated through additional experiments using actual driving environments or driving simulators.

Given these limitations, the following research will be designed in phases. This study served as an exploratory phase, validating the relative visibility differences between LED lighting and retroreflective materials in a controlled experimental environment. Through this, the basic effectiveness of LED lighting was established, and a foundation was provided for more comprehensive follow-up research. The following validation research phase will include the following verification items. First, the sample size will be expanded to at least 30 participants, including women, older drivers, novice drivers, and participants with corrected visual acuity of 0.8–1.0, thereby securing demographic diversity. A varied sample would encompass different age groups, genders, and experience levels, providing a more comprehensive understanding of the clothing's visibility and usability across the entire spectrum of motorcycle riders. This broader demographic approach would also allow for the assessment of the gear's efficacy across various body types and riding styles, which may influence visibility and recognition distances. Second, field validation will be conducted in actual road environments encompassing various lighting conditions (presence or absence of street lighting), road types (urban/rural), and weather conditions (clear, rain, fog). Conducting field tests in multiple settings, such as urban streets, rural roads, and during different times of the day and varying weather conditions, would yield more robust data. By measuring detection distance during constant-speed driving, the differences between simulation results and actual driving will be quantified, and the effects of environmental factors on visibility will be analyzed. Such data would be invaluable in determining the performance of LED and retroreflective protective clothing in real-life situations, providing insights that are critical for the practical application of research findings. These studies could also explore the interplay between LED and retroreflective gear and other visibility aids, such as motorcycle lighting systems, to determine the most effective combination of safety features. Third, gradient experiments will be conducted to systematically adjust LED parameters, including luminance, flicker frequency, and color combinations, to derive

conditions that provide maximum visibility. Fourth, by measuring the time and distance from the point of recognition to reaction initiation, braking initiation, and complete stop in driving environments, the driver response-inducing effects of LED-illuminated protective clothing will be analyzed. This can serve as foundational data for evaluating the potential accident prevention contribution of such equipment. This phased approach is designed to accumulate empirical evidence regarding the visibility and safety of protective equipment and to contribute to future product design and standard development. In conclusion, future research, equipped with a broader scope and real-world applicability, has the potential to substantively impact the design of protective motorcycle clothing and, consequently, the safety of riders on the road.

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References

1. Clemente-Suárez, V.J.; Navarro-Jiménez, E.; Moreno-Luna, L.; Saavedra-Serrano, M.C.; Jimenez, M.; Simón, J.A.; Tornero-Aguilera, J.F. The impact of the COVID-19 pandemic on social, health, and economy. *Sustainability* **2021**, *13*, 6314. [[CrossRef](#)]
2. Beckers, J.; Weekx, S.; Beutels, P.; Verhetsel, A. COVID-19 and retail: The catalyst for e-commerce in Belgium? *J. Retail. Consum. Serv.* **2021**, *62*, 102645. [[CrossRef](#)]
3. Nguyen, S.T.; Moeinaddini, M.; Saadi, I.; Cools, M. Unveiling the drivers of modal switch from motorcycles to public transport in Southeast Asia. *Transp. Res. Part F Traffic Psychol. Behav.* **2024**, *102*, 373–391. [[CrossRef](#)]
4. Fujita, M. The rise of local assemblers in the Vietnamese motorcycle industry: The dynamics and diversity of industrial organization. In *Vietnam's Economic Entities in Transition*; Palgrave Macmillan: London, UK, 2013; pp. 146–166.
5. Sykes, D.; Kelly, K.G. Motorcycle drive tourism leading to rural tourism opportunities. *Tour. Econ.* **2016**, *22*, 543–557. [[CrossRef](#)]
6. Li, Y.; Qiu, J.; Liu, G.D.; Zhou, J.H.; Zhang, L.; Wang, Z.G.; Zhao, X.C.; Jiang, Z.Q. Motorcycle accidents in China. *Chin. J. Traumatol.* **2008**, *11*, 243–246. [[CrossRef](#)] [[PubMed](#)]
7. Sumit, K.; Ross, V.; Brijs, K.; Wets, G.; Ruiter, R.A. Risky motorcycle riding behaviour among young riders in Manipal, India. *BMC Public Health* **2021**, *21*, 1954. [[CrossRef](#)] [[PubMed](#)]
8. Kwan, I.; Mapstone, J. Visibility aids for pedestrians and cyclists: A systematic review of randomised controlled trials. *Accid. Anal. Prev.* **2004**, *36*, 305–312. [[CrossRef](#)]
9. Robbins, C.J.; Fotios, S. Motorcycle safety after-dark: The factors associated with greater risk of road-traffic collisions. *Accid. Anal. Prev.* **2020**, *146*, 105731. [[CrossRef](#)]
10. Wood, J.M. Improving the conspicuity and safety of pedestrians and cyclists on night-time roads. *Clin. Exp. Optom.* **2023**, *106*, 227–237. [[CrossRef](#)]
11. Simović, S.; Ivanišević, T.; Trifunović, A.; Čičević, S.; Taranović, D. What affects the e-bicycle speed perception in the era of eco-sustainable mobility: A driving simulator study. *Sustainability* **2021**, *13*, 5252. [[CrossRef](#)]

12. Wood, D.P.; Glynn, C.; Walsh, D. Motorcycle-to-car and scooter-to-car collisions: Speed estimation from permanent deformation. *Proceedings of the Institution of Mechanical Engineers, Part D. J. Automob. Eng.* **2009**, *223*, 737–756. [[CrossRef](#)]
13. Moberly, N.J.; Langham, M.P. Pedestrian conspicuity at night: Failure to observe a biological motion advantage in a high-clutter environment. *Appl. Cogn. Psychol. Off. J. Soc. Appl. Res. Mem. Cogn.* **2002**, *16*, 477–485. [[CrossRef](#)]
14. de Rome, L.; Ivers, R.; Fitzharris, M.; Du, W.; Haworth, N.; Heritier, S.; Richardson, D. Motorcycle protective clothing: Protection from injury or just the weather? *Accid. Anal. Prev.* **2011**, *43*, 1893–1900. [[CrossRef](#)] [[PubMed](#)]
15. de Rome, L. Could wearing motorcycle protective clothing compromise rider safety in hot weather? *Accid. Anal. Prev.* **2019**, *128*, 240–247. [[CrossRef](#)] [[PubMed](#)]
16. Porchia, B.R.; Baldasseroni, A.; Dellisanti, C.; Lorini, C.; Bonaccorsi, G. Effectiveness of two interventions in preventing traffic accidents: A systematic review. *Ann. Ig.* **2014**, *26*, 63–75.
17. Basar, M.F.; Razik, N.H.A. Increase Visibility for Motorcyclist Detection at Night for the Purpose of Avoiding Accidents Using a Simple RF Circuit. *Int. J. Appl. Phys. Math.* **2013**, *3*, 217. [[CrossRef](#)]
18. Wu, D.; Hours, M.; Ndiaye, A.; Coquillat, A.; Martin, J.L. Effectiveness of protective clothing for motorized 2-wheeler riders. *Traffic Inj. Prev.* **2019**, *20*, 196–203. [[CrossRef](#)]
19. de Rome, L.; Ivers, R.; Fitzharris, M.; Haworth, N.; Heritier, S.; Richardson, D. Effectiveness of motorcycle protective clothing: Riders' health outcomes in the six months following a crash. *Injury* **2012**, *43*, 2035–2045. [[CrossRef](#)]
20. Robusto, C.C. The cosine-haversine formula. *Am. Math. Mon.* **1957**, *64*, 38–40. [[CrossRef](#)]
21. Norman, G. Likert scales, levels of measurement and the laws of statistics. *Adv. Health Sci. Educ.* **2010**, *15*, 625–632. [[CrossRef](#)]
22. de Winter, J.C.F.; Dodou, D. Five-Point Likert Items: T test versus Mann-Whitney-Wilcoxon. *Pract. Assess. Res. Eval.* **2010**, *15*, 11.
23. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, 7th ed.; AASHTO: Washington, DC, USA, 2018.
24. Olson, P.L.; Sivak, M. Perception-response time to unexpected roadway hazards. *Hum. Factors* **1986**, *28*, 91–96. [[CrossRef](#)] [[PubMed](#)]
25. Samson, C.J.R.; Hussain, Q.; Alhajyaseen, W.K.M. Analysis of stopping sight distance (SSD) parameters: A review study. *Procedia Comput. Sci.* **2022**, *201*, 126–133. [[CrossRef](#)]
26. Kováčsová, N.; de Winter, J.C.F.; Schwab, A.L.; Christoph, M.; Twisk, D.A.M.; Hagenzieker, M.P. Riding performance on a conventional bicycle and a pedelec in low speed exercises: Objective and subjective evaluation of middle-aged and older persons. *Transp. Res. Part F Traffic Psychol. Behav.* **2016**, *42*, 28–43. [[CrossRef](#)]
27. Vera-Uribe, E.M.; Armenta, J.S.; Baez Perez, D.A.; Rodriguez, M.D. Validation of Computerized Tools Developed to Collect Data on Safety Driving: A Pilot Study. In *Proceedings of the 2023 IEEE International Conference on Computer Science and Engineering (ENC)*, San Luis Potosi, Mexico, 11–13 September 2023; pp. 1–6.

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