Optical Engineering

RESEARCH PAPER

Investigating the impact of laser dazzling on shooting performance in a simulator environment: baseline scene

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ABSTRACT. Our study examines how laser dazzling affects human performance, specifically accuracy and reaction times, using a laser dazzling shooting simulator at the Royal Military Academy, Belgium. The research assesses the performance degradation under laser dazzling in a simple, baseline scene, including different target contrasts and the use of laser eye protection. Utilizing a 532 nm green laser for a safe yet effective dazzle, trained shooters' performances were measured and analyzed. The results align strongly with a live shooting trial and correlate with Adrian/CIE visibility levels. Additionally, electrical brain activity data, acquired via electroencephalography (EEG), provided insights into the shooters' mental states. EEG-derived metrics, particularly frontal alpha asymmetry and frontal alpha power, revealed that participants experienced heightened negative and avoidance emotions, coupled with increased cognitive load prior to shooting. These responses returned to baseline levels postshooting. Moreover, distinct cognitive and emotional states were observed in relation to different types of laser eye protection goggles, potentially correlating with variations in shooting performance. These findings pave the way for future research with more advanced simulation scenes and deepen understanding of the effects of laser dazzle.

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Keywords: laser dazzling; shooting simulator; human performance; cognitive and emotional state; electroencephalography

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1 Introduction

Laser dazzling, the technique of using visible light lasers to interfere with human vision or degrade optical sensor operations, has gained increasing relevance in military, law enforcement, and aviation sectors. As a nonlethal countermeasure, understanding how laser dazzle affects human performance is of particular interest. Although there are several models and simulations that evaluate the impact of laser dazzle on the human eye,[1–7] few studies have examined its effects on human task performance.[8–13] This paper aims to provide insights into this subject, presenting findings from laser dazzling trials conducted using a shooting simulator.

As part of the NATO SET-249 task group,[14] we conducted two measurement campaigns at the Royal Military Academy in Brussels in 2021 and 2022. These trials, serving as baseline

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explorations in a simulator environment, aimed to investigate the shooting performance of trained shooters when dazzled by green laser light at 532 nm. The 2021 trials were designed to approximate a live shooting range trial[13] with the purpose of validating our shooting simulator's results.

The 2022 trials expanded the scope, exploring various parameters like target contrasts and ballistic goggles, and introduced electrical brain activity data analysis via the electroencephalography (EEG) technique to assess the mental state of shooters, marking a novel aspect of this study.

Herein, "mental state" refers particularly to cognitive and emotional distress, which influence mental workload—defined as the mental cost incurred while performing a specific task. This workload is dependent on factors like task difficulty, individual skills, and perception.[15,16] Such distress, manifesting as anxiety or worry, can negatively impact performance[17,18] by reducing the processing and storage capacity of working memory, thereby increasing on-task effort.[19] Due to its high temporal resolution, EEG has shown potential in detecting these mental states, with alpha power activity being used as a marker for stressful situations.[20]

This approach, including comparisons with live shooting data and visibility level (VL) calculations, lays the baseline for future advancements of the simulator. Building on these results, we aim to progress toward more realistic scenes in the future. This will involve gradually incorporating more complex elements, such as target recognition, identification, tracking, and realistic backgrounds enhancing the applicability of results from simulator trials.

2 Methodology

2.1 Shooting Simulator

Our shooting simulator[21,22] featured a dark tunnel closed off at one end by a projection screen, a projector (Epson EH-TW9400W), a modified airsoft rifle equipped with an invisible infrared (IR) laser, an IR spot tracking camera, and a dazzling laser (see Fig. 1). The projector was used in its default configuration, with the color mode set to "natural," except for specific segments of the 2022 trials. For those, termed "DARK" settings in the 2022 trials (explained in the 2022 scenario description in Sec. 2.3), the projector's brightness and iris were set to their minimum levels to achieve the low-luminance levels as reported in Table 1.

For the dazzling of shooters, a modified GLARE MOUT Plus laser dazzler (200 mW, 532 nm, 6 mrad divergence, B. E. Meyers) was used, with its divergence increased to 150 mrad by attaching a lens. This resulted in a spot diameter of 0.5 m at the shooter's head position, resulting in a laser irradiance between 90 and 110 $\mu\mathrm{W/cm}^2$. The projected, simple, baseline scene simulated Olympic type bullseye targets at a distance of 25 m, with various contrast settings on a simple, gray background. The simulator software, developed within the unity game-engine platform, performed various functions including scene generation, laser spot tracking, and data storage.

An eye-safe 850 nm laser pointer (CPS850V, Thorlabs) was mounted on an M4A1 MWS assault rifle replica (Tokyo Marui) equipped with an iron sight. The laser spot on the projection screen was tracked by a camera (MAKO G-158B, Allied Vision equipped with a bandpass filter in front of the optics, centered around 850 nm), and the position and timing of the spot were registered into a database at every trigger event. Trigger events were generated by the depression of a momentary switch located beneath the weapon trigger, causing the target to disappear from the screen. No additional feedback was given to the shooters during these trials. An ESP32-based board fixed to the weapon managed laser operation, trigger and Wi-Fi communication with UNITY.

The target projection simulated 1-m diameter Olympic type bullseye targets at a distance of 25 m, comprising either concentric circles for the 25% and 0.5% target contrast settings, or concentric circles within a white square for the 100% target contrast setting, as shown in Fig. 2. The contrast settings of 100%, 25%, and 0.5% in the simulator correspond to opacity levels set in the unity game-engine, influencing how the gray background appeared through the black and white parts of the target. Consequently, these settings affected the overall perceived contrast. The actual contrast values, as experienced by the participants, are more accurately represented by the Weber contrast measurements provided in Table 1.

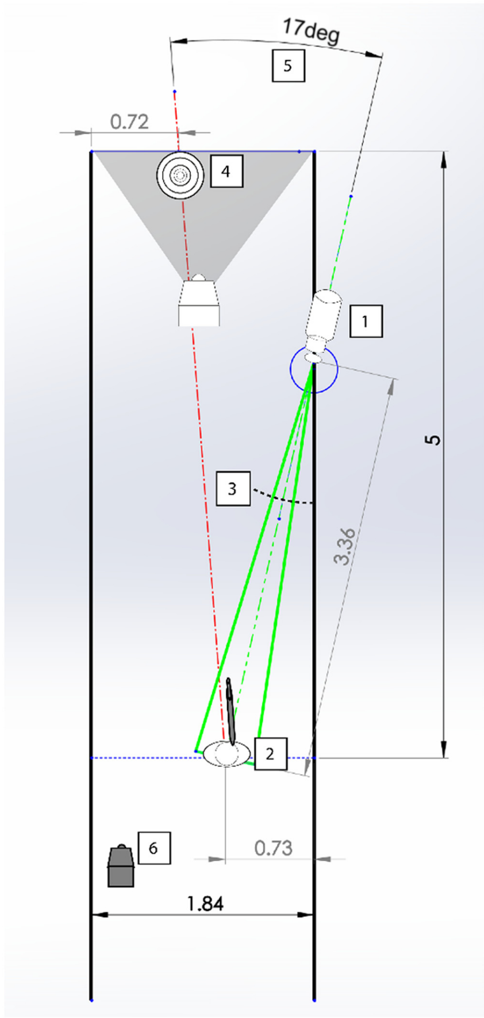


Fig. 1 Scheme of the shooting simulator: 1, dazzling laser; 2, shooter with modified gun; 3, beam from dazzling laser; 4, projected target; 5, dazzling angle; and 6, camera tracking the infrared spot of the weapon.

Table 1 Measured luminance levels of the different projected targets and calculated Weber contrast of the black target center with the white outer rings of the targets as well as the white outer rings of the target with the gray background. The terms "BRIGHT" and "DARK" are explained in the 2022 scenario description in Sec. 2.3.

					Weber contrast	
	Target contrast setting (%)	Black (target) (cd/m^2)	White (target) (cd/m^2)	Gray (background) (cd/m^2)	Black center with white outer of the target (%)	White outer of the target with gray background
BRIGHT 2022	100	5.1	119	27.7	–95.7	329.6
	25	12.36	59	27.7	–79.1	113.0
	0.5	27.25	28.28	27.7	–3.6	2.1
DARK 2022	0.5	0.543	0.58	0.557	–6.4	4.1
BRIGHT 2021	100	5	140	30	–96.4	366.7

2.2 Electroencephalography–Photoplethysmography Headband

During this trial, a sensorized headband was worn by the majority of the shooters (limited by logistical considerations). The sensorized headband was in-house developed, based on the physiological signal acquisition platform BITalino.[23] It was comprised of a textile-based headband enclosure with dry metal electrodes that record the electrical brain activity via EEG in the left and right forehead (positions Fp1 and Fp2 in the 10/20 EEG electrode placement system, respectively). Additionally, the headband included an optical sensor that was placed on the left earlobe to record the blood-volume pulse [photoplethysmography (PPG)] signals. The collected EEG data were used to assess the shooters' mental (cognitive and emotional) state immediately before each shot, as well as 2 and 4 s after the shot.

2.3 Participants

The participants were Belgian military members with similar and adequate shooting experience. Prior to the trial, they were briefed on laser safety aspects, test protocol, and provided with an experimental protocol and consent form. None of the participants had experienced laser dazzle before these experiments, with the only exception being those who had participated in the 2021 trial and returned for the 2022 trials. The tests were approved by the Academic Ethical Committee Brussels Alliance for Research and Higher Education (Dossier Number B200-2021-098).

2.4 Test Protocol and Scenarios

The participants were given the following instructions as they entered the shooting tunnel one by one.

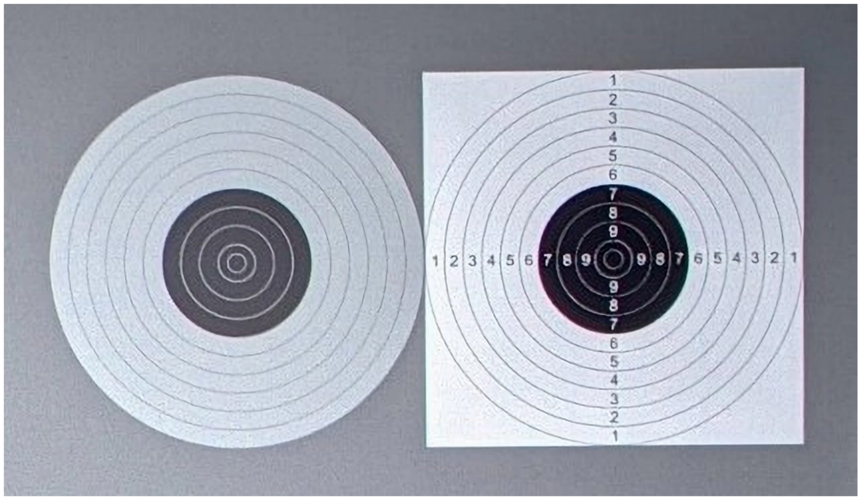
(1) Assume the standing shooting position above a cross marked on the floor, aim at the projection screen, and close your eyes to allow for the adjustment of the laser dazzler pointing direction.
(2) Take three zeroing shots without dazzling at ease at a white dot in the middle of the screen.
(3) Adopt a nonconventional resting position, which involved releasing the rifle with the nonfiring hand, leaning forward, looking at the floor, and resting the muzzle of the rifle on the cardboard box on the ground.
(4) Upon hearing a "BEEP" signal, quickly assume the standing shooting position, aim at the target, pull the trigger, yell "shot," and return to the nonconventional resting position.
(5) Wait for the next BEEP signal.

Additionally, participants were advised not to look directly at the laser to avoid any potential degradation in shooting performance due to the aftereffects of laser dazzle. Although not specifically monitored, direct gazing at the laser by the shooters during the trials was not anticipated, given the instructions and the task's focus. Following each trial, participants were informally asked if they noticed any aftereffects, anything unusual, or any discomfort. They reported not having noticed any aftereffects. No formal postparticipation interviews were conducted.

During the 2021 campaign trials, the BEEP signal was repeated every 10 s, which was determined on the bases of a preliminary trial, to allow the shooters ample time to take the shot without unnecessarily prolonging the trial. In the 2022 campaign trials, the next BEEP signal followed 10 s after the previous shot was registered (within a set).

Shooters were exposed to the laser only while aiming and taking their shots. Upon hearing the BEEP signal, they quickly assumed the shooting position, aimed, fired, and then returned to looking at the ground, thereby minimizing their exposure to the laser. This process meant that the actual exposure duration to the laser was slightly shorter than the reported shooting delay values, as these included the time taken to assume the shooting position. Although the laser was activated 1 s before each BEEP signal, the shooters were still looking at the floor in the nonconventional resting position and they were not actively exposed to the laser. Additionally, the laser was turned off after each shot was taken and remained off until 1 s before the next BEEP signal.

To prevent muscle memory effects, the targets were presented in quasirandom horizontal positions, and the nonconventional resting position (release the rifle with the nonfiring hand,



(a) (b)

Fig. 2 Photo of (a) the 25% contrast target and (b) the 100% contrast target. The 0.5% contrast target (not shown) had the same shape as the 25% contrast target.

lean forward, look at the floor, and rest the nozzle of the rifle on the cardboard box on the ground) was enforced between shots.

In the 2021 campaign trials, participants were tasked with completing two sets of a shooting sequence while wearing either standard ballistic goggles (LEP0) or prescription glasses. The two sets comprised 8 and 7 shots, respectively, with a 100% contrast target appearing in the various quasirandom horizontal positions (as shown in Fig. 2) against a bright gray background. The first two shots in the first set and the first shot in the second set were taken without laser dazzling, whereas the remaining shots were taken with the target appearing at dazzling angles of 17 deg, 11 deg, 8 deg, and 6 deg. Collectively, this resulted in three shots without dazzling and three shots at each dazzling angle. The quasirandom angular positions of the target relative to the dazzling laser for both sets are detailed in Table 2.

In the 2022 campaign trials, participants undertook four shooting sequence sets, featuring different ballistic goggles. Notably, the first set involved alternating among three goggle types—LEP0 (standard transparent goggles without laser protection), LEPX, and LEPY (both providing 532 nm laser protection but with LEPY having a lighter tint than LEPX) in a random order. During this set, participants executed three shots per goggle type, targeting a 0.5% low-contrast target. The targets were positioned in quasirandom horizontal locations against a "DARK" low-luminance backdrop. This setup did not involve any laser dazzling, focusing instead on participants' ability to perceive and aim at the less visible targets.

The subsequent three sets (each with a different pair of goggles) consisted of five shots each, with targets appearing at different contrast levels and quasirandom horizontal positions on a brighter background (referred to as "BRIGHT"). The quasirandom contrast and angular positions of the targets relative to the dazzling laser for these three sets are presented in Table 3. The aim

Table 2 Dazzling angles of the projected targets in chronological order during the 2021 campaign trials. The high-contrast target projection was used for all shots.

Order of shots	1	2	3	4	5	6	7	8
First set	No laser 100%	No laser 100%	Laser on 17 deg 100%	Laser on 8 deg 100%	Laser on 17 deg 100%	Laser on 6 deg 100%	Laser on 11 deg 100%	Laser on 8 deg 100%
Second set	No laser 100%	Laser on 11 deg 100%	Laser on 6 deg 100%	Laser on 17 deg 100%	Laser on 11 deg 100%	Laser on 8 deg 100%	Laser on 6 deg 100%	

Table 3 Dazzling angles and contrast levels of the projected targets during the 2022 trials for the BRIGHT condition, presented in chronological order for each set of goggles.

Order of shots	1	2	3	4	5
LEP0 set	No laser 0.5%	Laser on 17 deg 25%	Laser on 8 deg 25%	Laser on 11 deg 25%	Laser on 6 deg 25%
LEPX set	No laser 0.5%	Laser on 6 deg 25%	Laser on 17 deg 100%	Laser on 11 deg 25%	Laser on 6 deg 0.5%
LEPY set	No laser 0.5%	Laser on 17 deg 100%	Laser on 6 deg 0.5%	Laser on 11 deg 25%	Laser on 6 deg 25%

Table 4 Dazzling angles and contrast levels of the projected targets during the preliminary 2022 trial, presented in chronological order for each set of goggles.

Order of shots	1	2	3	4	5	6	7	8	9	10
LEP0 set	No laser 11 deg 25%	No laser 6 deg 100%	Laser on 17 deg 25%	Laser on 8 deg 100%	Laser on 11 deg 100%	Laser on 6 deg 25%	Laser on 11 deg 25%	Laser on 6 deg 100%	Laser on 8 deg 25%	Laser on 17 deg 100%
LEPX set	No laser 17 deg 25%	No laser 8 deg 25%	Laser on 11 deg 25%	Laser on 6 deg 100%	Laser on 17 deg 100%	Laser on 8 deg 25%	Laser on 11 deg 100%	Laser on 6 deg 25%	Laser on 17 deg 25%	Laser on 6 deg 100%

with these sets was to compare the performance with 25% contrast targets under LEP0 against the 100% contrast targets from the 2021 trials and to observe the variations in performance between different LEPs across various target VLs at given dazzling angles.

To aid in the preparation for the main 2022 campaign trials, a preliminary trial involving only four shooters was conducted. Each shooter completed two sets of a shooting sequence: one set while wearing LEP0 goggles and a second set while wearing LEPX goggles. The quasirandom contrast and angular positions of the targets relative to the dazzling laser for these sets are provided in Table 4. Although these measurements were excluded from the primary statistical analysis of shooting scores and delays to maintain a balanced dataset between LEPX and LEPY conditions, they contributed valuable data for the limited mental state statistical analysis dataset.

During a NATO SET-249 meeting held in Brussels, an additional measurement trial was conducted with four shooters. The primary objective was to present the main 2022 campaign scenarios to the group members. Although this measurement set replicated the conditions of the main campaign trials, its data were not included in the main statistical analysis of shooting scores and delays, in order to maintain a focused assessment. However, it played a crucial role in the mental state statistical analysis, contributing to the augmentation of our limited dataset in that aspect. It is important to acknowledge that the shooters were aware of being observed via camera feed during this trial, potentially introducing a performance bias. Despite this potential influence, the data collected remained valuable and relevant for the mental state statistical analysis.

2.5 Participants and Data Collection

In the 2021 campaign trials, 30 participants joined, including 7 left-handed and 23 right-handed shooters, resulting in 428 recorded shots out of a potential 450. Exclusions comprised five participants without ballistic goggles for the primary score and delay analysis. Instances impacting the analysis included four unattempted shots due to the dazzle. For these, zero scores were assigned, and the shooting delays were recorded as missing values in the statistical analysis. Two shots following the unattempted shots were not correctly registered due to our lack of preparedness for this eventuality, and both the score and delay values were discarded in the statistical analysis. Subsequent shooters were instructed to "shoot into the ground" when unable to take a shot, verbally inform the staff, and return to a nonconventional resting position. There was one misfire due to hardware issues. An outlier shooter with extended response times was excluded. Additionally, five participants with prescription glasses were treated statistically as goggle wearers due to performance equivalence.

In the 2022 campaign trials, there were 19 participants, 9 of whom did not participate in the 2021 campaign trials. All shooters wore the provided ballistic goggles, and those requiring prescription corrections wore contact lenses underneath the goggles. Two of the 19 participants were left-handed, a subset of the 7 left-handed shooters from 2021. There was one instance of an unattempted shot due to the dazzle, resulting in a zero score and missing value for the shooting delay in the statistical analysis. There was also one instance where the gun did not register the trigger action and one instance of a software glitch, which left out one target position. Excluding the first shots with each pair of goggles in the DARK shooting set, which were considered as "training" shots, there were 397 correctly registered scores and 396 correctly registered shooting delay values.

For logistical reasons, sensorized headband EEG data were recorded for only 14 out of the 19 participants in the 2022 main trial. To augment this restricted dataset, we incorporated data from the preliminary 2022 trial (four shooters, with three also participating in the main 2022 trial) and the NATO group meeting showcase trial (four distinct shooters, with three also involved in the 2022 trial) into the statistical analysis. There were some instances of recorded data being noisy due to suboptimal headband fitting on the shooters. Overall, we were able to include a total of 675 observations in the statistical analysis. These observations were relatively evenly distributed among data points representing the mental state conditions just before the shot, 2 s after the shot, and 4 s after the shot.

2.6 Mental State Analysis Indicators

In the current paper, we focused on two indicators computed from the recorded EEG data, representative of the cognitive and emotional state of the shooter: frontal alpha power and the frontal asymmetry index. To obtain these indicators, we computed the arithmetic mean power spectral density of each EEG channel (Fp2 and Fp1) for the alpha frequency band (8 to 12 Hz) using the Welch's method (Hamming window of 8 segments of the length signal with 50% overlap, and 256 points), via an in-house developed signal processing script.[24] The power spectrum was computed individually for the three time intervals: 2 s just before the shot, 2 s after the shot, and 4 s after the shot.

The frontal asymmetry index measures the difference in the alpha power between the left and right frontal regions, and is computed as

$$\text{frontal asymmetry index} = \text{alpha power}\,\mathrm{Fp2} - \text{alpha power}\,\mathrm{Fp1} \tag{1}$$

with Fp1 and Fp2, corresponding to electrode positions in the left and right hemisphere, respectively.

Frontal asymmetry has been associated with emotional valence (positive versus negative) and motivation (attractive versus avoidance).[25] Previous studies found that decreased left alpha power is related to positive valence or an approach-oriented behavior, whereas decreased right alpha power is related to negative valence or avoidance.[26,27] Consequently, a more positive frontal asymmetry index has been associated with more emotional control, whereas a more negative frontal asymmetry index suggests a lack of emotional control. These relationships were already observed in a shooting task, performed under pressure, which resulted in a more negative asymmetry index and decreased shooting accuracy compared to the nonstressed condition.[28]

Additionally, the frontal alpha power was also computed as

$$\text{frontal alpha power} = \text{alpha power}\,\mathrm{Fp2} + \text{alpha power}\,\mathrm{Fp1}. \tag{2}$$

The frontal alpha power has been associated to cognitive load, showing higher values in a more demanding task than in a low demanding task (mental arithmetic).[29,30]

Herein, the alpha power values were normalized to the mean of "baseline" values acquired during the 2 s before the BEEP sound signals instructing the shoots. In this manner, mental state changes due to the subsequent shooting tasks could be more accurately assessed.

2.7 Statistical Analysis

For the statistical analysis of shooting scores and delays, we combined data from the 2021 trial and the 2022 BRIGHT conditions sets, since they involved similar shooting tasks and shared some participants. We analyzed the 2022 DARK dataset separately. For this primary analysis, we excluded the first shots from each set, which were intended as training shots, as well as data from the five participants who completed the trials without ballistic goggles or prescription glasses in the 2021 trials. The remaining data were analyzed using a linear mixed model also accounting for repeated measures, which included the score and delay of each shot. We encoded these measures using the dazzling angle, target contrast, the protection goggles used, trial identification, and the number of repeated shots under the same conditions in a given trial by a shooter. To address the correlation between repeated measures, we used a first-order autoregressive structure with heterogenous variances. We found that variances of shooting scores and delays were significantly larger for difficult shots (e.g., those at a 6 deg dazzling angle) compared to easy shots (e.g., those at a 17 deg dazzling angle). We also observed a strong correlation between results at nearby angles, which decreased as angles became more distant, which justified using the autoregressive structure. The fixed effect of the model included the interaction of dazzling angle, target contrast, worn goggles, and trial identification. Dazzling angles and contrast values were treated as ordinal variables, whereas worn goggles and trial identification were treated as nominal variables. We also tested including the interaction of the repeated variable as a parameter in the fixed effect, but it had no effect on the estimated marginal means produced by the model. To account for individual differences in shooting ability, we treated each shooter as a subject in the model, with a random specific intercept included.

For the 2022 DARK dataset analysis, we followed a similar approach to that used for the 2021 trial and 2022 BRIGHT conditions data. The first shot from each set, intended as a training shot, was excluded from this analysis. We encoded the repeated measures of shooting scores and delays based on the protection goggles used and the number of times a shot was repeated under the same conditions by a shooter in a given trial.

Initially, we considered a first-order autoregressive structure to address the correlation between repeated measures, as in the case of the 2021 and 2022 BRIGHT dataset. However, our analysis indicated that a scaled-identity structure was sufficient. In our model, the fixed effect was the type of protection goggles used. We also tested including the interaction between goggles and repeated shots, but this was not significant for either shooting scores or delays.

As with our previous analyses, individual shooters were included as subjects in the model, with a random intercept to account for variations in shooting ability.

For the statistical analysis of the frontal asymmetry index and frontal alpha power indicators, we combined data from the main 2022 BRIGHT condition trials, the 2022 preliminary trials, and the 2022 NATO meeting showcase trial. Similar to the shooting score and delay statistical analysis, we excluded data from the first shots in each set, which were considered training shots. The remaining data were subjected to a linear mixed model. This model encompassed frontal asymmetry index and frontal alpha power values for each shot at three measurement moments: just before the shot; 2 s after the shot; and 4 s after the shot. These measures were encoded based on dazzling angle, target contrast, protective goggles used, and the measurement moment.

Consistently with the shooting score and delay analysis, a first-order autoregressive structure with heterogeneous variances was employed. The fixed effect of the model involved the interaction of dazzling angle, target contrast, worn goggles, and the measurement moment. Dazzling angles and contrast values were treated as ordinal variables, while worn goggles and the measurement moment were considered nominal variables. Each shooter was treated as a subject in the model. However, due to convergence issues, a random specific intercept for each subject could not be included. Consequently, this limitation may have contributed to larger error bars and the possibility of some false negatives.

3 Results and Discussion

3.1 Shooting Scores and Delays

Figure 3 depicts a subset of calculated estimated marginal means values across the various levels of the fixed variables, from the 2021 and main 2022 trials (under BRIGHT settings). The shown

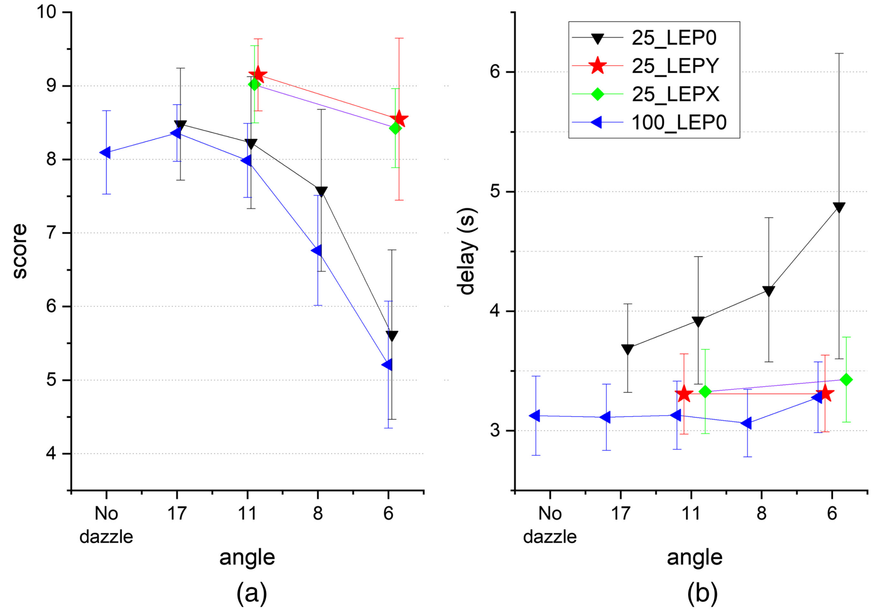


Fig. 3 Subset of the estimated marginal means of (a) scores and (b) delays from the 2021 and main 2022 campaigns as estimated by the linear mixed model. Error bars stand for 95% confidence intervals. Codes shown in the legend represent the contrast of the target followed by the designation of the worn goggles. The curves are slightly offset on the *x*-axis for visual clarity.

error bars correspond to the 95% confidence intervals of these estimated marginal means, directly informing on the statistical significance of differences.

Analysis of the LEP0 (transparent ballistic goggle) 100% target contrast data reveals that shooting scores are significantly lower at the 6-deg dazzling angle compared to the "no laser dazzle," 17-deg, and 11-deg dazzling angles. Shooting scores appear to remain statistically equivalent at the 11-deg and larger dazzling angles. Although the differences are statistically insignificant, the highest shooting scores were obtained at the 17-deg dazzling angle, rather than at the expected no laser dazzle level. Notably, shooting scores at the 17-deg dazzling angle are significantly higher than those at the 8-deg and 6-deg dazzling angles. Furthermore, the analysis of the 100% target contrast delays shows that there were no statistically significant differences in shooting delays across different dazzling angles.

Regarding the LEP0 25% target contrast data, shooting scores are significantly lower at the 6-deg dazzling angle compared to the 17-deg and 11-deg dazzling angles. Inspection of the 25% target contrast delays reveals that while they are not significantly different at the 95% confidence level at the different dazzling angles (mainly because of the large variance at small dazzling angles), they are systematically longer at smaller dazzling angles.

When comparing the estimated marginal means of the LEP0 ballistic goggle 25% target contrast shots with those of 100% target contrast shots, we consistently observe higher scores for the 25% target contrast, although without reaching statistical significance. Conversely, shooting delays consistently increase for the 25% target contrast and show statistically significant rises at the more challenging dazzling angles (6-deg and 8-deg dazzling angles).

Importantly, the 25% target contrast data were collected during the 2022 trials, whereas the 100% target contrast data were gathered in the 2021 trials. In the 2022 trials, the initial shots in each set featured demanding 0.5% contrast targets. In contrast, the 2021 trials began with easily visible 100% contrast targets, without laser dazzling. Additionally, the 2022 trial introduced a first set featuring low-background luminance and low-target contrast (DARK). One could speculate that the heightened demands of the initial targets in the 2022 trial may have driven shooters to adopt a slower and more careful and accurate shooting approach, however, the shots taken while wearing LEPX or LEPY were taken just as quickly (within error bars) as the shots during the 2021 campaign trials. More likely, the similar trend in scores for both target opacities across dazzling angles might indicate a deliberate speed-accuracy trade-off[31] mainly driven by the degree of laser dazzle, rather than the visibility of the target.

Further analysis of the estimated marginal means of scores and delays for the 25% target contrast shots taken while wearing LEPX or LEPY ballistic goggles with laser eye protection, reveals that both effectively mitigate the impact of laser dazzling within the studied range of conditions. Noticeably, elevated scores and shooting delays as short (within error bars) as the shortest ones achieved with the LEP0 transparent goggles for 100% contrast targets are achieved. The performance with LEPX and LEPY remains statistically indistinguishable at both the 11-deg and 6-deg dazzling angles for the 25% contrast target shots.

3.2 Emotional/Mental State Indicators

Figure 4 shows the time courses of the frontal asymmetry index and the frontal alpha power for two different participants wearing the three types of goggles (LEP0, LEPX, and LEPY) during the shooting task at the 11-deg dazzling angle and 25% contrast target.

The frontal alpha asymmetry is typically more negative for LEP0 than for LEPX and LEPY before the shot, then trending to zero and then increasingly negative from 2 to 4 s. On the other hand, after the shot, the frontal alpha asymmetry for LEPX and LEPY trends to zero (i.e., it trends to the baseline levels at 2 s before the "BEEP" sound signal). The frontal alpha power is higher for LEPX than for the other two goggles, while the LEPY goggles show values closer to zero (or baseline levels). For the LEP0 and LEPX goggles, there is a trend in the frontal alpha power: power goes up before the shot and gradually decreases, which may be related to the mental state change from preparation to resolution of the task. Overall, this figure illustrates how dynamic the shooting task is.

In the context of the BRIGHT dataset, Fig. 5 illustrates the estimated marginal means of frontal asymmetry index and frontal alpha power, collapsed across the various dazzling angles, target contrasts, and worn ballistic goggles, at the three different measurement moments, and for all participants. Notably, the most negative frontal asymmetry index and the highest frontal alpha power values are observed just before the shot, i.e., 2 s before the shot (a time window that translates the immediate preparation of the shot). Following the shot, a distinct declining trend is evident for both indicators, with frontal asymmetry becoming significantly less negative and frontal alpha power significantly reduced by 4 s after the shots, approaching the baseline values. Overall, results suggest that before the shot, participants had a more negative emotional valence or sense of avoidance toward the task, as well as a higher cognitive load, than after the shot, probably resulting from the anticipation of addressing a demanding task. These results seem

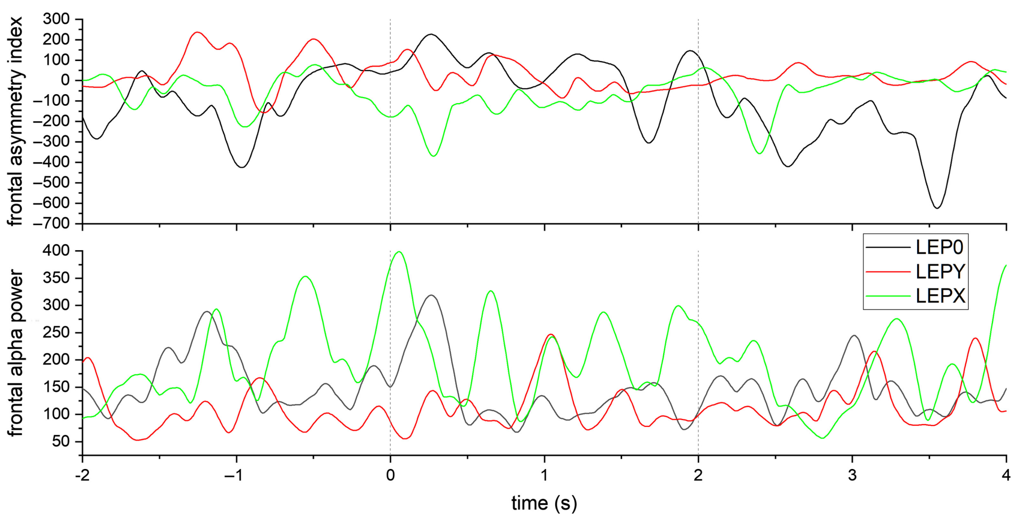


Fig. 4 Exemplar frontal alpha asymmetry and frontal alpha power time courses during the shooting task at 11-deg dazzling angle and 25% target contrast, for two different participants and the three types of goggles (LEP0, LEPX, and LEPY). The time courses cover the three measurement moments: before the shot (−2 to 0 s) and 0 to 2 s and 2 to 4 s after the shot.

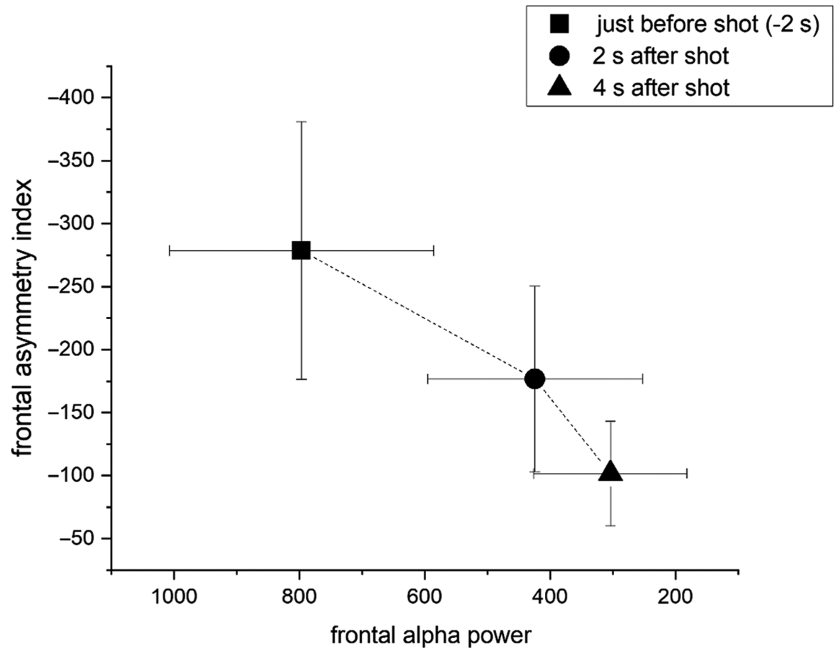


Fig. 5 Estimated marginal means of frontal asymmetry index (*y* scale) and frontal alpha power (*x* scale) collapsed over all fixed factors except the measurement moments, for all participants. Error bars stand for 95% confidence intervals. Symbols shown in the legend represent the measurement moments.

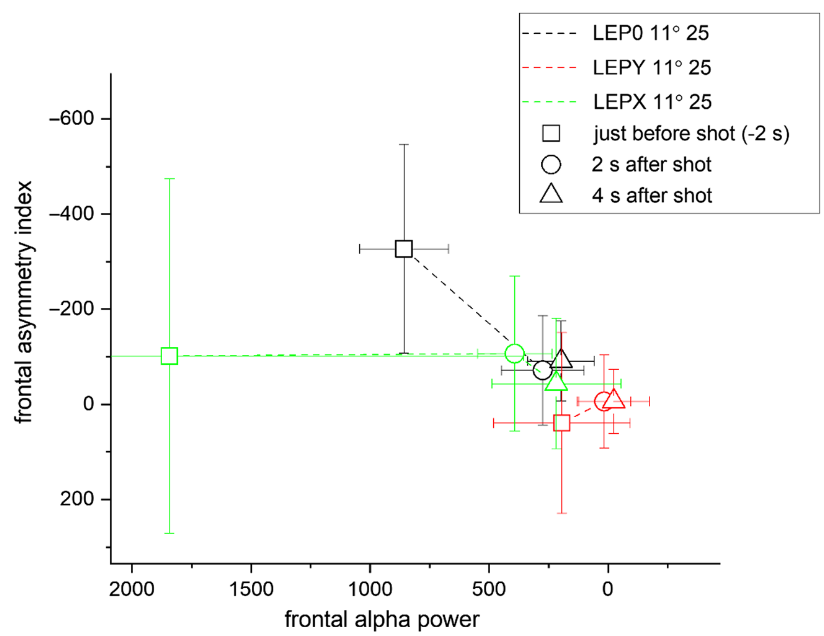


Fig. 6 Estimated marginal means of frontal asymmetry index (*y* scale) and frontal alpha power (*x* scale) at 11-deg dazzling angle and 25% target contrast for the three different ballistic goggles at the three measurement moments for all participants. Error bars stand for 95% confidence intervals. Symbols shown in the legend represent the measurement moments, and the colors stand for the different goggles.

to agree with the literature in which more demanding tasks are associated with more a negative frontal asymmetry index and higher frontal alpha power.

Figure 6 illustrates the estimated marginal means at the 11-deg dazzling angle and 25% target contrast, focusing on the three different ballistic goggles across the three measurement moments, for all participants. Despite relatively substantial error bars overall, for LEP0 goggles, the frontal alpha power just before the shot is significantly higher compared to both 2 and 4 s after the shot. This trend aligns with the overall pattern observed. In contrast, the sizeable error bars associated with frontal asymmetry index estimations hinder significant comparisons within any LEP. Among the different LEPs, it is noteworthy that the frontal asymmetry index just before the shot with LEP0 goggles is significantly more negative than the values at 2 and 4 s after the shot when wearing LEPY goggles, while the frontal alpha power is significantly higher than values at 2 and 4 s after the shot when wearing LEPX and LEPY and notably, also significantly higher than the estimated value for LEPY just before the shot.

Results suggest that the cognitive and emotional states moments just before the shots are associated with shooting performance. In particular, when wearing the LEP0 goggles, participants showed a more negative frontal asymmetry index or emotional valence and sense of avoidance than when using the LEPX and LEPY goggles, which could be associated to lower scores and longer delays. Conversely, when wearing the LEPY goggles, participants showed a more positive frontal asymmetry index or valence and sense of approach than when using the other goggles, and concomitantly showed higher scores and shorter delays (although not significantly different from the performance when wearing the LEPX goggles).

Additionally, when wearing the LEP0 and especially the LEPX goggles, participants showed much higher frontal alpha power just before the shots than in comparison with when wearing the LEPY goggles and the baseline values. These findings may be related to a higher cognitive load experienced with the former goggles as these showed no filter to dazzling (LEP0) or used a stronger light filter (LEPX) than LEPY, which seemed to reduce the overall visibility. Nonetheless, given that shooting performances were similar when wearing LEPX or LEPY, it seems that participants adapted well to both types of light filters.

In Figs. 5 and 6, it is also observed that, after the shots had taken place, both asymmetry and frontal alpha power values approach the baseline values (0, 0). In particular, it seems that wearing the LEPY goggles results in cognitive and emotional states more similar to the baseline state across all three measurement moments, which may suggest a more "natural" usage of such goggles. Nonetheless, it must be pointed out, that the baseline values are not obtained with participants at rest but already engaged in the task. Consequently, their cognitive and emotional states during the moments prior to the BEEP sound signals are also relevant for shooting performance.

3.3 Results from the Low-Background Luminance (DARK) Sets

In the 2022 trials, we conducted a distinct set of measurements under the DARK conditions, featuring extremely low-target contrast at 0.5%, without laser dazzling and with low background luminance. This set was designed to evaluate the performance impact of different ballistic goggles (LEP0, LEPX, and LEPY) under these low-VL conditions. The initial shots with each pair of goggles were omitted, being considered as training due to the unfamiliarity of the shooters with the low-contrast targets.

Figure 7 displays the estimated marginal means of scores and shooting delays for the DARK dataset. An examination of the plot indicates that there were no statistically significant differences in shooting scores when comparing the various goggles under DARK conditions. However, there are statistically significant differences in shooting delays: delays were significantly shorter with LEP0 goggles compared to LEPX, while LEPY goggles resulted in intermediate delays. The difference in delays is consistent with the lighter tint of LEPY goggles relative to LEPX, suggesting an influence on visibility and response time.

3.4 Comparison of the 2021 Simulator Trial with a Live Shooting Trial

Our 2021 shooting simulator campaign aimed to closely replicate the conditions of a live shooting trial (detailed in Ref. 13). This live trial was conducted on an indoor shooting range using an assault rifle-type weapon. The 2021 simulator trial setup matched the laser irradiance, dazzling angles, background luminance, and the use of standard ballistic goggles (LEP0) with the high-contrast target with the live shooting trial's conditions. However, we diverged in two aspects: first, to better explore conditions where the dazzling effect was strong, we omitted the 22-deg dazzling angle present in the live trial and introduced the 8-deg dazzling angle. Second, during the live shooting campaign, shooters turned their backs to the target after each shot, firing five

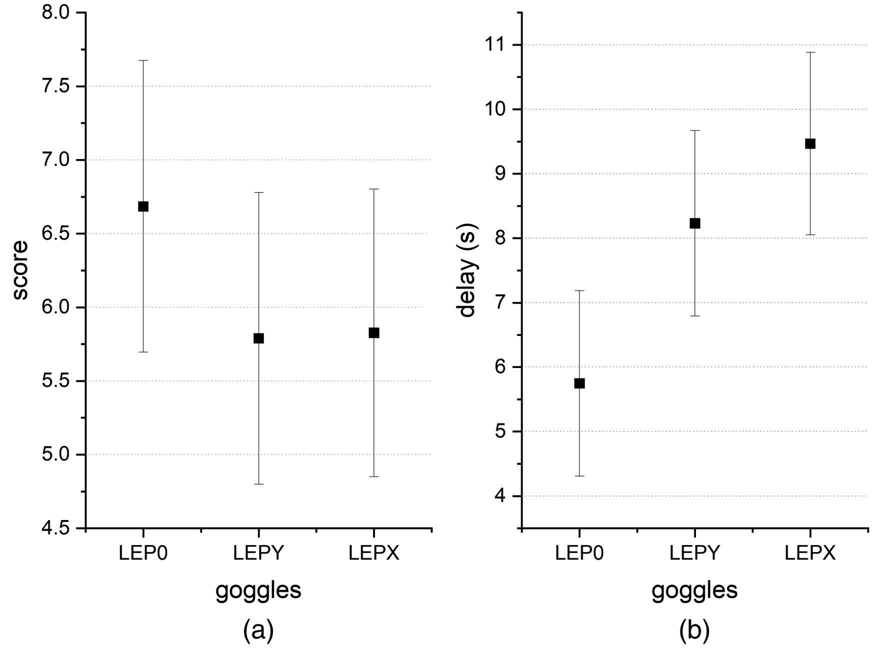


Fig. 7 Estimated marginal means of (a) scores and (b) delays as estimated by the linear mixed model (model 4) from the "DARK" dataset. Error bars stand for 95% confidence intervals.

consecutive shots at the same dazzling angle and target. Replicating this turning movement in the simulator was not feasible. To test if the nonconventional resting position disrupted muscle memory similarly to the turning movement, we organized a preliminary simulator campaign. In this campaign, shooters were instructed to fire at the same target position consecutively, taking the nonconventional resting position between shots. We found that this did not disrupt muscle memory sufficiently, leading to higher scores and shorter delays for subsequent shots, which was opposite to what we observed in the live trial where scores decreased and delays increased systematically from shot 1 to shot 5 (as seen in Fig. 8). To address this, we implemented quasirandom target position sequences, which effectively eliminated any systematic patterns in the data in chronological order or for shots at the same target position.

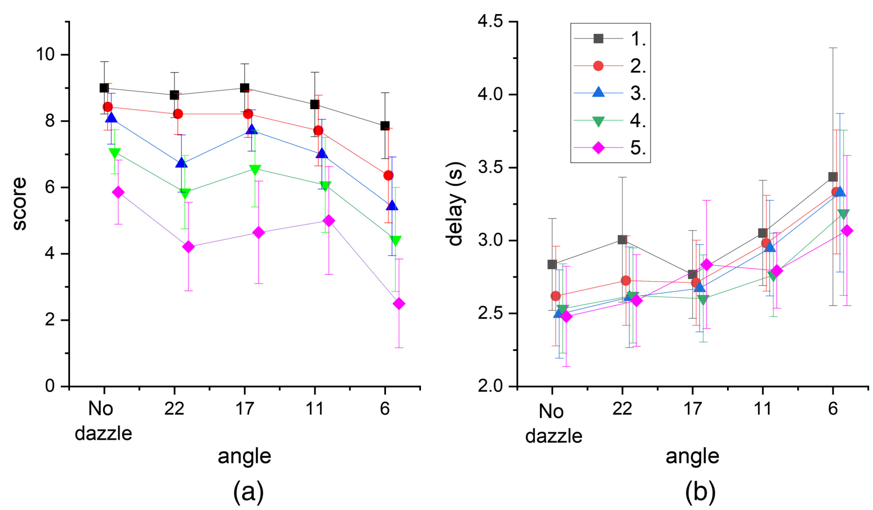


Fig. 8 Estimated marginal means of (a) scores and (b) delays from the live shooting trial.[13] Each curve represents the mean score or delay for one of the five consecutive shots fired at the target, from shot 1 (black) to shot 5 (magenta). The curves are offset slightly on the *x* axis for visual clarity. Error bars stand for 95% confidence intervals.

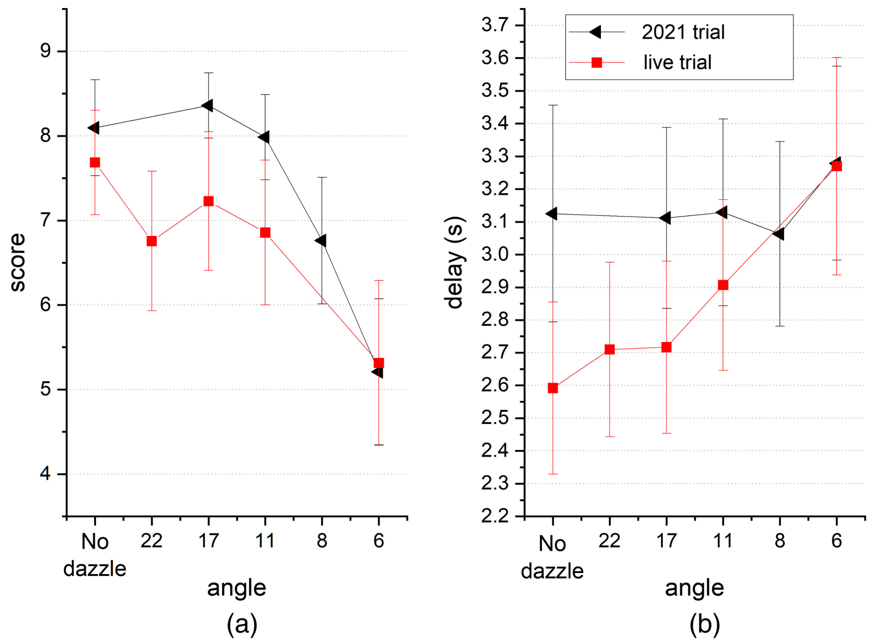


Fig. 9 Estimated marginal mean shooting (a) scores and (b) delays for the 100% contrast target and standard ballistic goggles, obtained from the 2021 shooting simulator trial (shown in black), as well as the estimated marginal means from the live shooting trial[13] (shown in red). The error bars stand for 95% confidence intervals.

A linear mixed model was applied to reanalyze the raw data from this live trial, providing estimated marginal means values with 95% confidence intervals (see Fig. 8) for an easy comparison with the results from our simulator trial.

Figure 9 compares the estimated marginal means for shooting scores and delays between the 2021 campaign and the live trial. The data from the live trial were collapsed over consecutive shots, offering a visual comparison of shooting performance under similar conditions. Despite the differences in protocols, the estimated marginal means of scores from both trials showed a strong agreement, notably aligning at the 6-deg dazzling angle, where the dazzling effect was strongest. Delays, while showing some variation, overlapped reasonably well and coincidentally perfectly overlap at the 6-deg dazzling angle.

3.5 Comparison with Visibility Level Calculations

Based on the measured luminance levels of the targets and background (Table 1), we calculated the VL of the white outer rings against the gray background and the black center against the white outer rings using the Adrian/CIE visibility model: VL calculator.[32] VL is calculated as the ratio of the actual target contrast ($\Delta L_{\mathrm{actual}}$) to its predetermined contrast detection threshold ($\Delta L_{\mathrm{threshold}}$):

$$\mathrm{VL} = \frac{\Delta L_{\mathrm{actual}}}{\Delta L_{\mathrm{threshold}}}. \tag{3}$$

The estimates were calculated for a 20-year-old observer (mean age of the trial participants) with brown eyes and assumed a 2-s target viewing duration. The calculation used a glare illuminance of 566 lux, which corresponds to the 100 $\mu\mathrm{W/cm^2}$ mean laser irradiance at the eyes of the shooters at 532 nm.

The resulting VLs of the white outer rings against the gray background reflect the difficulty of spotting the target before aiming the gun. On the other hand, the VLs of the black center of the target against the white outer rings represent the actual aiming through the iron sight of the gun. When the gun was centered on the middle of the target, the view through the aperture sight was approximately restricted within the white outer rings of the target.

Given the relatively constant shooting delays observed in the 2021 simulator trial results across various dazzling angles, it is reasonable to infer that the shooting scores reflect the challenge posed by laser dazzle. This makes the data from the 2021 trial ideal for comparison.

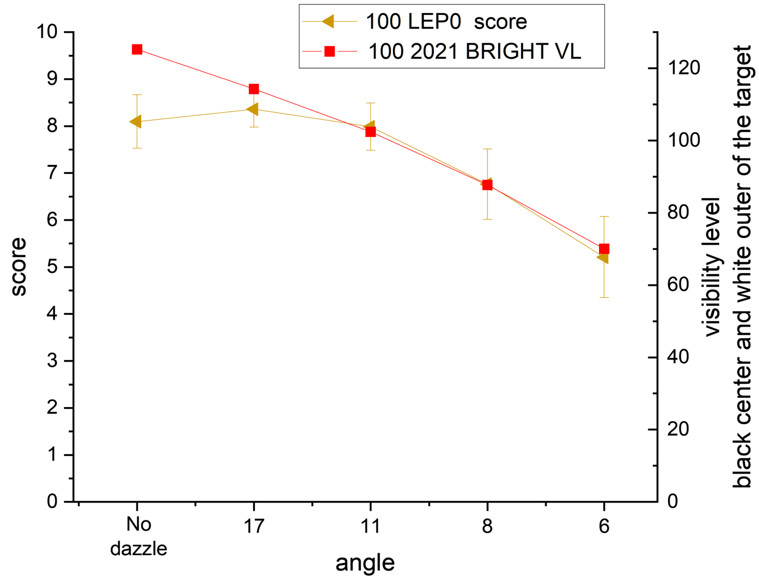


Fig. 10 Estimated marginal means of scores for the standard ballistic goggles (LEP0) and 100% contrast target (left scale) compared to the estimated VL for the inner black center of the target with the white outer rings in the corresponding conditions. Error bars for the scores stand for 95% confidence intervals.

Figure 10 provides a comparison between the estimated marginal mean scores and the corresponding calculated VLs. The left scale of the graph shows the estimated marginal mean scores, and the right scale displays the calculated VLs. This comparison reveals that for dazzling angles ranging from 6 deg to 11 deg, there is a linear relationship characterized by a slope of $\Delta y/\Delta x = 10/130$ and a zero intercept, effectively linking shooting performance with VL. For larger angles, however, the shooting scores tend to plateau, indicating a limit to the decreasing difficulty as measured by VL.

4 Conclusions

This study, using a laser dazzling shooting simulator at the Royal Military Academy, Belgium, contributes to the broader understanding of how laser dazzle affects human shooting performance, with a focus on accuracy and reaction times. Set in a simple, baseline scene, the research was designed to establish initial insights into the effects of laser dazzle in a controlled environment, providing a valuable starting point for more complex future studies and the development of virtual and augmented reality simulations.

In our trials, we employed a 532 nm green laser at irradiance levels significantly below (1/10th) the maximum permissible exposure. We observed that this level of laser dazzle, particularly at smaller dazzling angles, significantly affects shooting performance. Our findings, consistent across multiple datasets, align strongly with a live shooting trial conducted on a shooting range and correlate with VL calculations, underscoring the reliability of our simulator-based approach.

In the second phase of our research, we expanded our investigation to include lower contrast targets and different laser eye protection ballistic goggles. Our results showed that the effects of lower contrast were more pronounced in shooting delays under dazzle conditions than in shooting scores. The laser eye protection goggles effectively mitigated the impact of laser dazzling within our experimental conditions, only showing a degradation in shooting performance at the lowest contrast and luminance levels compared to transparent ballistic goggles without laser dazzle.

The EEG data collected during the trials provided valuable insights into the cognitive and emotional states of shooters, particularly when using different LEPs under laser-dazzling conditions. EEG-derived metrics, such as frontal alpha asymmetry index and frontal alpha power, revealed that just prior to shooting, participants exhibited more negative and avoidance feelings, as well as increased cognitive load. Subsequently, 4 s after the shot, their emotional and cognitive states returned to baseline, characterized by more positive and approach-oriented feelings, and a lower cognitive load. Distinct emotional and cognitive states were observed in participants when wearing the different goggles, especially before taking the shots, which could be correlated to shooting performance. A more negative frontal asymmetry index was associated with lower shooting scores and longer shooting delays, as seen with transparent ballistic goggles. In contrast, higher frontal alpha power correlated with lesser visibility in more tinted ballistic goggles with laser eye protection, yet a more "natural" or baseline-like response was noted with less tinted laser eye protection goggles. Both types of goggles with laser eye protection allowed the shooters to maintain comparable shooting performance. Further studies are warranted to assess additional EEG-derived metrics, such as engagement and attention, as well as sympathetic responses, such as heart rate and breathing rate, as derived from PPG signals.

Looking forward, the foundational data gathered from this simple scenario will be instrumental in guiding more advanced research. Our next steps involve incorporating more complex elements into the simulation, such as target recognition and tracking, as well as more realistic backgrounds and targets, to further deepen our understanding of laser dazzle effects in varied contexts.

In summary, this study not only contributes to the current understanding of laser dazzle but also lays the groundwork for practical applications in tactical and training environments. The insights gained can inform the development of more effective training protocols and the design of protective gear, enhancing operational safety and performance under laser-dazzling conditions. The progression toward more sophisticated simulations promises not just to broaden our understanding of laser dazzle but also to directly impact how military and law enforcement personnel are prepared for such scenarios.

5 Appendix

5.1 Linear Mixed Effect Models: SPSS Syntax

The variables in the models are as follows.

(1) negAngle: The dazzling angles (17-deg, 11-deg, 8-deg, 6-deg with 90 standing for the no dazzling laser condition), recoded by multiplying by −1, so that the reference category became the 6-deg angle. The reason for this was that the highest number of observations was at this angle, ordinal variable.
(2) contrast: target contrast, ordinal variable.
(3) goggles: worn googles, nominal variable.
(4) campaignID: trial identification, nominal variable.
(5) repeated: repetitions of a shot under the same condition in a given trial by a shooter, scale variable.
(6) at: measurement moment identification, nominal variable.
(7) shooter_id: participant identification, nominal variable, subjects of the model.
(8) delay_s: dependent, scale variable.
(9) score: dependent, scale variable
(10) asym: frontal asymmetry index, dependent, scale variable.
(11) arou: frontal alpha power, dependent, scale variable.>

5.2 Score

```
MIXED score BY negAngle contrast goggles campaignID
    /CRITERIA=DFMETHOD(SATTERTHWAITE) CIN(95) MXITER(100) MXSTEP(10)
SCORING(1)
    SINGULAR(0.000000000001) HCONVERGE(0, ABSOLUTE) LCONVERGE(0,
ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
    /FIXED=negAngle*contrast*goggles*campaignID | SSTYPE(3)
    /METHOD=REML
    /PRINT=CPS CORB DESCRIPTIVES HISTORY(1) SOLUTION TESTCOV
    /RANDOM=INTERCEPT | SUBJECT(shooter_id) COVTYPE(VC) SOLUTION
    /REPEATED=negAngle*contrast*goggles*repeated*campaignID |
SUBJECT(shooter_id) COVTYPE(ARH1)
```

```
    /EMMEANS=TABLES(negAngle*contrast*goggles)
    /EMMEANS=TABLES(OVERALL).
```

5.3 Delay

```
MIXED delay_s BY negAngle contrast goggles campaignID
    /CRITERIA=DFMETHOD(SATTERTHWAITE) CIN(95) MXITER(100) MXSTEP(10)
SCORING(1)
    SINGULAR(0.000000000001) HCONVERGE(0, ABSOLUTE) LCONVERGE(0,
ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
    /FIXED=negAngle*contrast*goggles*campaignID | SSTYPE(3)
    /METHOD=REML
    /PRINT=CPS CORB DESCRIPTIVES HISTORY(1) SOLUTION TESTCOV
    /RANDOM=INTERCEPT | SUBJECT(shooter_id) COVTYPE(VC) SOLUTION
    /REPEATED=negAngle*contrast*goggles*repeated*campaignID |
SUBJECT(shooter_id) COVTYPE(ARH1)
    /EMMEANS=TABLES(negAngle*contrast*goggles)
    /EMMEANS=TABLES(OVERALL).
```

5.4 Frontal Asymmetry Index

```
MIXED asym BY at negAngle contrast goggles
    /CRITERIA=DFMETHOD(SATTERTHWAITE) CIN(95) MXITER(500) MXSTEP(100)
SCORING(1)
    SINGULAR(0.000000000001) HCONVERGE(0, ABSOLUTE) LCONVERGE(0,
ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
    /FIXED=goggles*contrast*negAngle*at | SSTYPE(3)
    /METHOD=REML
    /PRINT=CPS CORB COVB DESCRIPTIVES G LMATRIX R SOLUTION TESTCOV
    /REPEATED=goggles*contrast*at*negAngle*campaignID | SUBJECT(shooter_id)
COVTYPE(ARH1)
    /EMMEANS=TABLES(at)
    /EMMEANS=TABLES(at*goggles)
    /EMMEANS=TABLES(at*contrast*goggles)
    /EMMEANS=TABLES(at*negAngle*contrast*goggles)
    /EMMEANS=TABLES(OVERALL).
```

5.5 Frontal Alpha Power

```
MIXED arou BY at negAngle contrast goggles
    /CRITERIA=DFMETHOD(SATTERTHWAITE) CIN(95) MXITER(500) MXSTEP(100)
SCORING(1)
    SINGULAR(0.000000000001) HCONVERGE(0, ABSOLUTE) LCONVERGE(0,
ABSOLUTE) PCONVERGE(0.000001, ABSOLUTE)
    /FIXED=goggles*contrast*negAngle*at | SSTYPE(3)
    /METHOD=REML
    /PRINT=CPS CORB COVB DESCRIPTIVES G LMATRIX R SOLUTION TESTCOV
    /REPEATED=goggles*contrast*at*negAngle*campaignID | SUBJECT(shooter_id)
COVTYPE(ARH1)
    /EMMEANS=TABLES(at)
    /EMMEANS=TABLES(at*goggles)
    /EMMEANS=TABLES(at*contrast*goggles)
    /EMMEANS=TABLES(at*negAngle*contrast*goggles)
    /EMMEANS=TABLES(OVERALL).
```

Disclosures

The authors have no relevant financial interests in the manuscript and no other potential conflicts of interest to disclose.

Code and Data Availability

The data supporting the findings of this study, involving laser dazzling shooting simulator experiments, are not publicly available due to participant privacy and concerns regarding the potential misuse of sensitive information. Researchers interested in accessing the data can request it directly from the corresponding author at tomas.foldes@mil.be.

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