Design and development of a low-cost mask-type eye tracker to collect quality fixation measurements in the sport domain

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Abstract

The aim of the study was to build a low-cost mask-type eye tracker with accuracy and precision levels similar to those reported for commercial eye tracking devices. To this end, head-mounted hardware was designed and developed, while open-source software was modified for digital image capture, manipulation, and fixation analysis. An image recognition application was also included with different lighting scenarios. Moreover, parallax and viewing perspective errors were controlled to ensure the quality of data collection. The device was wireless and lightweight (99 g) to allow for natural movement and avoid participant discomfort. After calibration of a 9-target monocular grid, spatial accuracy and precision of the eye tracker was evaluated by 30 participants, at four different lighting setups, both before and after a climbing task. Validity tests showed high levels of accuracy in all conditions as evidenced by a systematic error for a 13-target grid of < 0.5º. The reliability tests also showed consistent measurements with no differences in accuracy recorded between participants, lighting conditions and visual behaviors for the pre- vs. post-climbing task. These results suggest that the present eye tracker reports spatial accuracy similar to other commercial systems with levels of high quality. Altogether, this innovative user interface is suitable for research purposes and/or performance analysis in physical activity and sport related activities. Also, features of this mask-type eye tracking system make it a suitable perceptual user interface to investigate human-computer interactions in a large number of other research fields including psychology, education, marketing, transportation, and medicine.

Keywords: Eye tracking, Visual Search behaviors, Wearable technology, Open-source, Accuracy, Precision, Climbing.

1. Introduction

Eye trackers refer to any system or set of monitoring tools that allow registration of the direction of gaze, the dilation of the pupil, or a combination thereof, in participants completing a perceptual-motor task. Trackers provide a constant flow of information about the participant in real time, enabling researchers to evaluate mental processes or identify stimuli that participants focus on[1]. Similarly, trackers record the positions of the pupil through cameras. This position data is then transformed into coordinates on computer screens[2].

Gegenfurtner, Lehtinen, and Säljö[3], conducted a meta-analysis on the gaze-tracking systems in different professional domains (e.g., sports, medicine and transport). Results showed that experts, in relation to novices, use longer and fewer fixations in the most relevant areas of the visual display.

However, even though it is an appreciable natural user interface for analysing visual behaviors of users[4], several constraints have prevented greater integration of eye trackers into the study of daily tasks. For example, these constraints include the lack of robustness or availability, high software price[5], or limited use to indoor activities[6]. Also, the use of special elements (e.g., lenses, electrodes, markers) attached to the eyes or skin, the need to keep the head still or transport of heavy equipment via a backpack containing the software and video camera on the back during the recording process has led to early fatigue in participants, unduly influencing research outcomes[7].

Video-based systems, particularly those attached to the user's head, are the most commonly used[8] since they reduce invasiveness and use small cameras with high resolution and sampling rates. These systems are based on detection of the main features of the eye.

The main applications of the eye tracking systems have been to provide indicators of cognitive load, assessment of understanding of reading, material design, focus of attention and distraction, and analysis of human-computer interactions[9], but the high price of these devices make them unaffordable for many research and practitioner groups. Low-cost, open-source eye trackers are mainly usable with desktop computer systems[5-10], incorporating most features of commercial systems, but at a lower price.

An additional concern is the quality of eye tracking data, which is not completely guaranteed[11]. Among the variables to consider during the collection of complex eye movement measures are the areas of interest, calibration, fixation duration, position of gaze, precision, and spatial accuracy[6]. Other factors to take into consideration during the calibration process are the type of eye tracker, experimental setup, lighting conditions, the participants' eye physiologies, visual aids, method of calibration, and operator[12]. Specifically, a limitation of some eye tracking devices is the requirement for participants to remain immobile, which limits the understanding of the role of vision during performance of complex actions (e.g., movement coordination in physical activity and sport). These tasks are rarely assessed due to the extreme costs associated with devices that permit participant mobility[13-14].

To avoid these limitations, studies should report aspects about data quality, such as whether a calibration process was undertaken, and if so, whether it reported system validity measures. Studies should also report optimal accuracy levels across all recording conditions and participants, as well as the criteria for excluding data.

The purpose of this study was to develop a low-cost, monocular system of registration and analysis of visual fixations, with similar levels of spatial accuracy as commercial systems. The main focus was to counter some of the problems alluded to in previous research studies using eye tracking systems, while seeking to develop quality criteria for system use and measurement. Specifically, the objectives of the study were to:

i) Design and develop a low-cost eye tracking hardware with commercially available cameras with an accuracy specification < 0.5º. The hardware also had to be mobile, wireless and lightweight, so that it does not interfere with performance of complex motor behaviors.

ii) Implement an open-source eye tracking software based on the Pupil system[15] that allows users to customize functions (e.g., direct display of visual fixations, handling the presentation of fixations), provides versatility (i.e., recognizes the pupil and reflection corneal with precision in different lighting conditions), and quickly registers visual fixations.

iii) Apply this eye tracker in analyses of performance in the sport domain. The developed system needed to have the capacity to register valid fixations with head and body movements, for example, during a climbing task.

Climbing was chosen as the task for this proof of concept study because it allowed for investigation of athletic performance in an individual sport which places participants at the limit of their physical capabilities. Many studies have examined gaze behaviors in sport performance dominated by team games. However, the climbing task allowed for examination as to how individual athletes perceive properties of a vertical surface for reach, grasp, and use of holds for quadrupedal locomotion[13]. Use of any additional equipment that might limit the field of view, restrict movement or influence the center of balance significantly increases the difficulty of the task[16]. Furthermore, variations in environmental conditions pose a challenge for video-based systems due to the presence of dust in the air and variable lighting conditions, such as low luminous light when climbing indoors versus bright sunlight when climbing outdoors[17].

2. Method

2.1 Participants

Thirty university volunteers without visual impairments, nor aids, took part in testing the calibration and validity of the developed eye tracker system. Participants provided informed consent according to the ethical standards of research of the University, accepting to participate voluntarily in the study. Participants received instructions about the task, but no specific information about the research hypothesis. Subsequently, five participants were selected randomly from the group and asked to perform the reliability test, measuring consistency in the accuracy of the device, before and after use in a climbing task. Another reliability test was also conducted under four different lighting conditions with a different group of five participants, again selected randomly.

2.2 Variables

The *accuracy* and *precision* of the eye tracker were measured because they are recognized as two of the most important properties for ensuring eye movement data quality[12]. Accuracy refers to the distance between the gaze location and the recorded positions (x, y) in the eye tracker data. Specifically, the *average fixation error* was quantified as the difference between an estimated gaze point and the true location of the calibration point[16]. This signified that the mean error value was averaged across 13-targets in the calibration test and 9-targets in the validation tests.

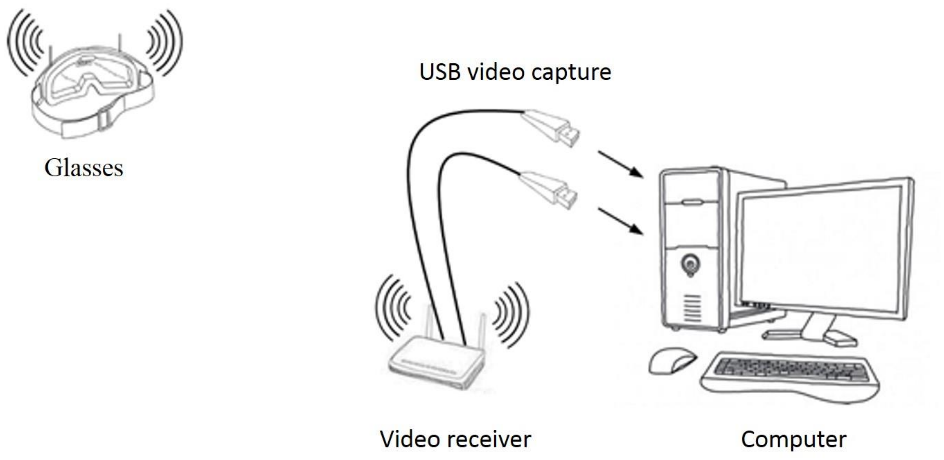
The variance in accuracy data was calculated (i.e., the variance in gaze position data when participants repeatedly fixated on the same points)[10]. In particular, the *spatial precision* of the system was quantified[16]. To estimate this *precision* level, the standard deviation was computed using the intraclass correlation coefficient (ICC) as a relative measurement[18] and limits of agreement (LoA) as an absolute measurement[19-20] because the majority of the data showed a normal distribution (see results section). To facilitate interpretation of the ICC value, Bland-Altman graphics were also required.

2.3 Hardware design

Two previous prototypes of eye tracker systems were tested before the final design version. First, a device was designed with an arm holding the eye camera as with some commercial eye tracker systems (e.g., ASL SE5000, EyeLink II, Eye Mark Recorder EMR-9, Dikablis Glasses) or other low cost systems (e.g., Dias Eye Tracker, Open Eyes, Pupil Headset). Benefits of this device included an accuracy level of 0.5º of visual angle, as well as a comfortable fit for the participants. However, fast head movements generated vibrations of the eye camera, and thus the positioning of the camera caused some unintentional contact with the hands.

In order to address and minimize the vibrations on the eye camera, a second compact design prototype was developed. The design was modelled after ski glasses, which allowed participants to wear the tracker on their faces. The lateral eye camera arm was replaced by another frontal mini-camera, thus increasing freedom of movement. The batteries were held in a separate box placed at the back of the head. However, the participants noted that the wire connecting the batteries to the device was uncomfortable. As a result, a third prototype was built with a more compact design, storing all components inside the glasses.

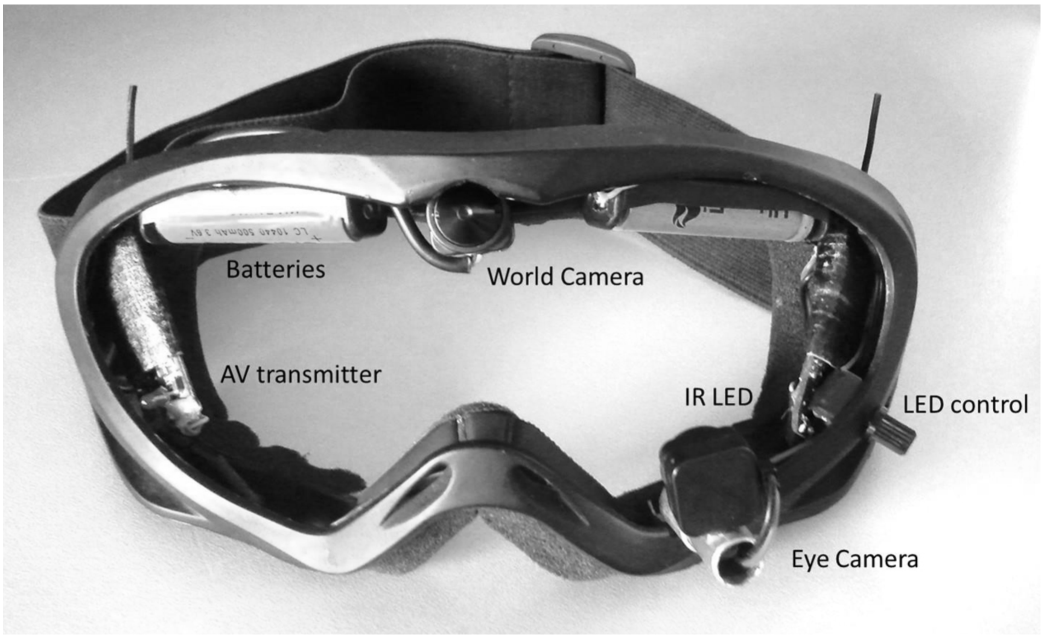
Two mini-cameras (30€ per camera) were used to capture videos, while a 2.4 Hz video transmission system (30€ per device) transferred the videos to a computer. This system provided an outdoor distance range of 100 m. As shown in Fig. 1, two USB Easycap DC60 STK1160 video recorders were attached to the computer to capture the video feeds and process the images.



The camera included the following features: 1/4CMOS (15.5 mm x 15.5 mm x 20 mm), 48 dB, 1 Lux/F2.8, video output 1.0V p-p/75 ohm, power supply DC 8V, and 45 mA.

To facilitate clear detection of the pupil, an 850 nm infrared LED was combined with a visible spectrum filter[20]. The lighting system was adjustable, allowing us to adjust the power of the LED to be adjusted when required by environmental performance conditions.

The structure of the glasses was modified to accommodate the front camera, video transmitters, and two micro-controllers. The glasses were also equipped with a small aluminium arm to allow adjusting the distance from the camera to the eye, as well as tilt it at different angles, so it would be able to adapt to the physiognomy of different participants. The device weighed 127 g with batteries included (99 g without them), making it one of the lightest systems currently available, and the smallest of the wireless and autonomous systems as shown in Fig. 2.



2.4 Software

The open-source software used, *Pupil* from Pupils-Labs[15], was programmed in Python, which made it relatively easy to modify and adapt[21]. Pupil uses *OpenCV*, a library providing multiple computer vision algorithms, which is open-source, so it can be used for research purposes[22]. The Pupil base code was modified to adapt it to the needs of the project.

2.4.1 Eye capture

The estimation of the gaze direction was based on pupil detection. Pupils were selected because their contour can be easily distinguished under IR light. Since they are circular, their contour approximates to an ellipse under perspective deformation. Therefore, the image processing module of the software detected pupils by finding ellipses in the images. The algorithm chosen was the RANSAC[23]. Open CV included *cv2.ellipse function*, which facilitated drawing an ellipse on the eye image coinciding with the ellipse defined by the edge of the pupil. To facilitate the process, a reduction in noise to each frame of the eye was applied by the *cv2.RGBtoGray function*, providing a grayscale image with better defined shapes and less heavy images to be processed. The corneal reflection was also removed and the black and white image was processed through the *cv2.threshold function*.

2.4.2 Calibration

Due to the rotation of the eyeball and the distortion caused by the lens of the camera (both the eye and the environment camera), the positions of the center of the pupil did not move linearly to the plane of the environment[24.] Therefore, the distortions induced in the image had to be calibrated and corrected[16].

After a review of different calibration methods[25], a 9-point based system was selected since it maintained a balance between accuracy and calibration comfort, while avoiding possible early fatigue in participants with shorter procedure durations[7].

2.4.3 Calibration process

After ensuring that the pupil shape was clearly detected, a sequential 9-points system-controlled calibration was performed. The calibration points were displayed sequentially in a predefined order.

The participant sat in front of the calibration pattern projected onto a screen at a distance of 4 meters. The participant's chin was resting on an adjustable support to the height necessary for the projection screen to be centered in front of the participant within the range of the world camera.

2.4.4 Collection of calibration data

A significant problem with the calibration is that the eye does not remain still before, during, or after looking at the point. For this reason, it is crucial to choose the right period in time to sample the coordinates of the eye image features[16]. When the front camera detected the shape of the calibration point, its position was recorded and linked to the position of the pupil detected in the eye camera.

When the program recorded a minimum of 250 valid calibration data points in the same marker position, a new location was chosen. For good measurement quality, a minimum ratio of valid points of 0.75 was selected[15].

Once the device was calibrated, the participant stood up and moved through the room. At that moment, video and audio data from the scene were captured, creating a list which contained the time intervals and the positions of the center of the pupil associated with each frame in the scene video.

2.4.5 Calibration distance

Both eyes are located in different positions, so participants received a slightly different image of the world scene on the retinae. This phenomenon, known as the Parallax effect[26-27] is exploited by the brain to estimate the distance to perceived objects. Due to the distance between the world camera and the eye of the participant, this phenomenon was taken into account in the process of validation.

2.5 Accuracy and precision of the device

Since a normal eye is never still due to microsacadic eye movements and observers have limited control to direct the gaze accurately at the target, it is important that the eye trackers improve performance accuracy to support the testing of strong scientific assertions[16].

A validity test was performed to quantify the difference between the real spatial points and the points registered by the eye tracker when the participant was required to gaze at these points. This validity test was carried out with a 13-target sample. To check the data consistency of spatial accuracy for the device, three precision tests were performed with different participants and lighting conditions, and also before and after a wall climbing task.

2.5.1 Validity test

After calibration, a screen was projected with 13-markers graduated in cm. Participants were asked to look at its center for 3 seconds, following a pre-set order of up-down and right to left. After calibration and recording, the relative positions of markers with the fixation points in the participants´ visual behaviors were compared.

The error caused by the perspective of viewing points was also taken into account to improve the validity of the data. The effect of perspective can cause a circle to be recorded in 2D as an ellipse, since the camera is perpendicular to the plane of the projection screen. To correct for perspective, real and perceived distances were calculated in order to extract the rate of correction for each of the points.

After calculating all local positions and their corresponding distances to the center of the marker, the average of deviations of each participant in each point was obtained. The average was obtained by the first 30 consecutive data series of 90 data of the metadata file generated by the software.

2.5.2 Reliability tests

Consistency in measurements

The stability of the device is essential to reflect real data values. It was necessary that the position of the cameras relative to the eyes did not vary during the execution of the participant, a condition achieved by the use of a head mounted system attached to the participant. Pre- and post-execution measurements were undertaken to check whether any differences occurred for the variables tested.

For this study, viewing and execution of a climbing route for a duration of one minute was selected. After calibration, participants executed the task on the climbing wall (Fig. 3). The climbing task included a rich mix of both static (e.g., maintaining balance on a hold) and dynamic functional movements (e.g., transferring weight between holds)[28], as well as occasional falls from the climbing wall onto the mats of the landing zone from a height of 3-4 metres. Then, the participant turned to the calibration-spot to complete the 13-marker test so that both eye records could be prepared.

2.5.3 Consistency in different lighting conditions

The opportunity for use in indoor and outdoor performance environments with precision is one of the most innovative features of the current eye tracker system. The capacity to detect the position of the pupil without problems in direct sunlight must take into consideration two limitations. First, an excess of sunlight may saturate the CMOS sensor of the camera's eye, resulting in useless white images. Second, default lighting can cause the outline of the pupil to be undistinguishable within the captured image of the eye. To adapt image acquisition to the characteristics of the environment, the eye tracker provided a variable resistor controlling the intensity of the eye tracker’s LED.

Four variations in lighting levels were established (Fig. 4): i) indoor low (i.e., lights - projection lighting only); ii) indoor high (i.e., lights on with high brightness); iii) outdoor low (i.e., cloudy day with diffuse sunlight), and iv) outdoor high (i.e., sunny day with direct sunlight).

2.6 Statistical analysis

The Kolmogorov-Smirnov test was carried out to check the variables distribution. To know if the values corresponding to the distance of separation between the position of the point recorded by the device and the center of the marker correspond to a normal distribution, the following conditions were used: i) the values mean of each 30 participant (30 participants * 30 data); ii) the mean of 5 participants in the lighting conditions (5 participants * 30 data by participant * 4 lighting conditions); and iii) the mean of 5 participants in different test application time (5 participants * 30 data by participants * 2 times) in each of the 13 points. A normal probability chart was used (i.e., q-q normal graph) as a normal contrast graphic technique.

To validate the device, the average distance of separation between the gaze location measured and each center of the 13 markers was calculated in the sample of 30 participants, 4 conditions of lighting, and before and after executing the climbing task. Such separation distances were displayed in degrees of visual arc.

A reliability analysis was requested to test the consistency of the measurement between participants, conditions of illumination and time (pre- vs post-) of climbing test. Specifically, the analysis of reliability of measures among participants was carried out through the use of standard deviation measures (ICC). To determine the reliability of the device between lighting conditions, and application of the test at recorded times, a repeated measures ANOVA test was used to check whether there were differences in accuracy between measurements.

An alpha level of < 0.05 was set for all analyses performed with the statistical package SPSS 21.0 (© 2012 SPSS Inc.). The program GraphPad Prism 6 was used to generate Bland-Altman graphics, as well as calculate the LoA and the difference or measurement error between measurements in each of three reliability tests.

3. Results

3.1 Normality data

The Kolmogorov-Smirnov test showed normality at 9 of the 13 separation distances between the gaze point and the center of the marker among the 30 participants. In the lighting test, 49 of 52 distances (13 points * 4 light conditions) reported normality, while in the climbing test, 25 of 26 distances (13 points * 2 tests) had a normal distribution. Based on these results, parametric statistics were used in further analyses. The Q-Q normal graph (see supplementary material) showed the difference between the empirical distribution of the data and its normal distribution.

3.2 Accuracy

Figure 5 shows the distance of separation between the gaze points registered with the device and the spatial position of the center of the 13 markers used for each one of the 30 participants. A point on the graph means the average value of 30 data per participant.

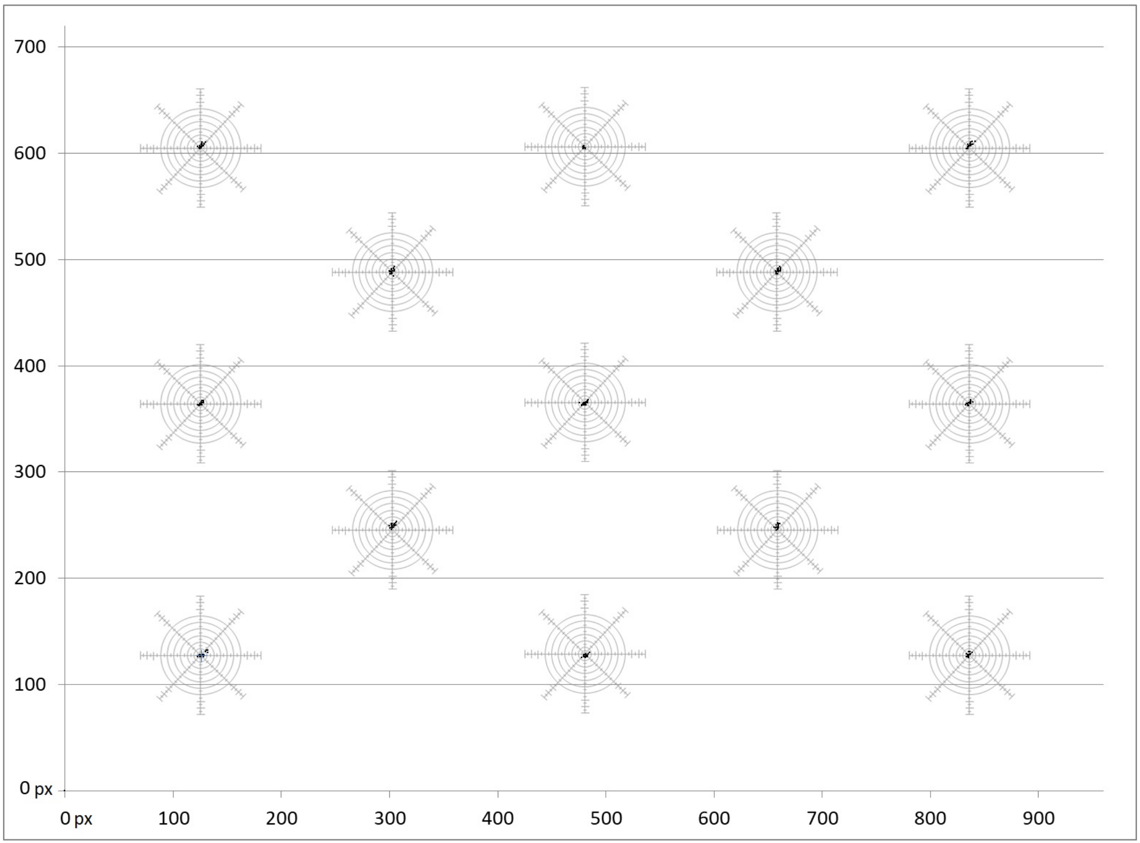
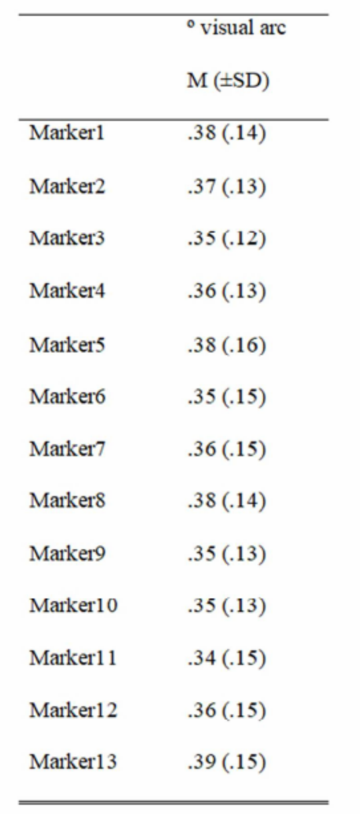


Table 1 shows the magnitude of these differences. The error value of 0.5° was not exceeded for any of the points. The mean of all the values in Table 1 was 0.36°.



	° visual arc M (±SD)
Marker1	.38 (.14)
Marker2	.37 (.13)
Marker3	.35 (.12)
Marker4	.36 (.13)
Marker5	.38 (.16)
Marker6	.35 (.15)
Marker7	.36 (.15)
Marker8	.38 (.14)
Marker9	.35 (.13)
Marker10	.35 (.13)
Marker11	.34 (.15)
Marker12	.36 (.15)
Marker13	.39 (.15)

Regarding the lighting test, Table 2 (see supplementary material) shows that the average differences were less than or equal to 0.35° for the illumination conditions at all fixation points.

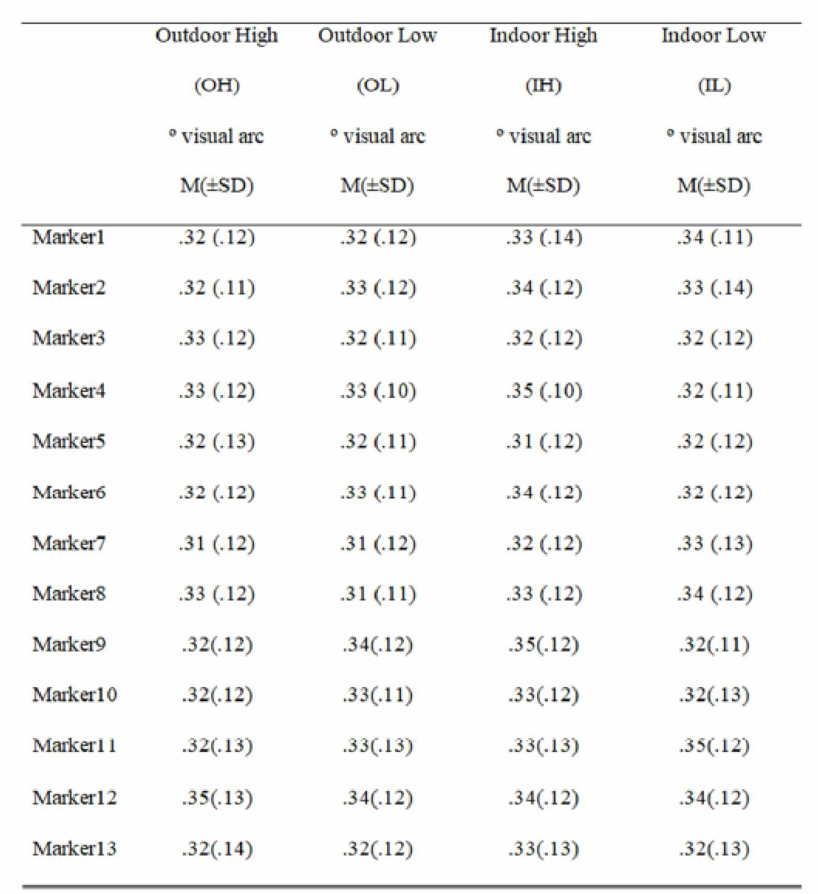
Specifically, the mean difference for all the points for a given lighting condition was 0.32° for OH and 0.33° for OL, IA, and IL. Regardless of points and illumination, the magnitude of these differences stood at 0.33°.

Relative to the climbing task, Table 3 (see supplementary material) shows the mean differences for five participants in a pre- and post-execution of the task. Specifically, the mean difference of the 13 points for both pre- and post-test was 0.31°.

3.3 Precision

3.3.1 Consistency between participants

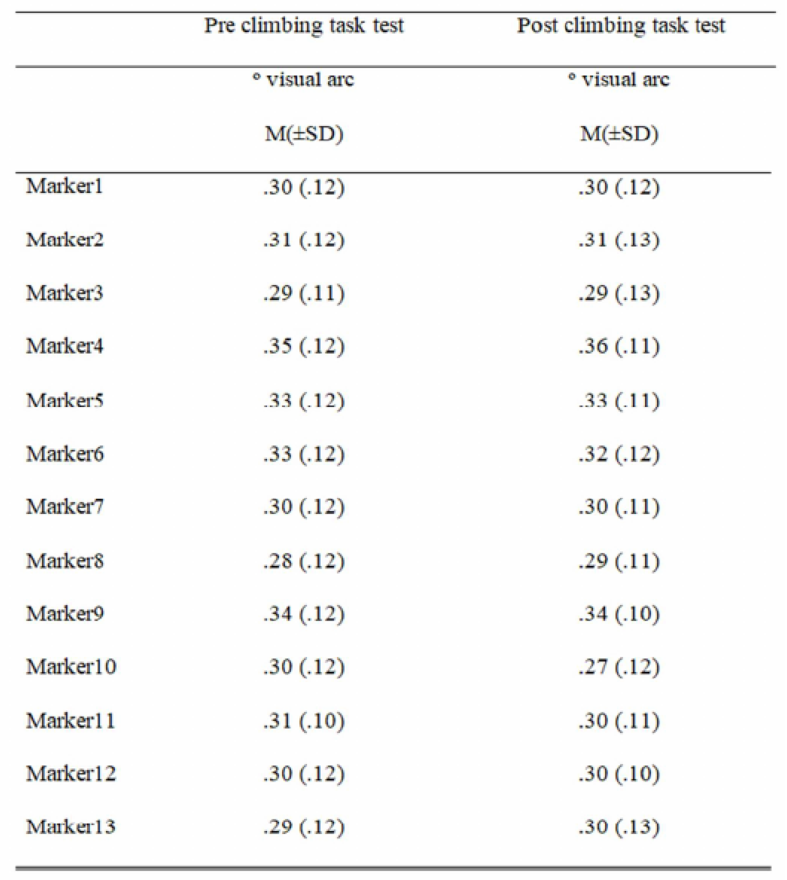
The reliability Cronbach’s alpha statistics showed that the ICC reached an average measure of 0.78 (lower limit 0.65 and upper limit 0.88) in the sample of 30 participants and 13 points. The average differences between pairs of validation points showed homogeneity (see supplementary material). Specifically, these average differences between gaze point and center of markers were always within the LoA established for that pair of points (see supplementary material). In addition, Bland-Altman graphics showed the visualization of pair comparisons between mean differences, mostly being distributed: i) randomly on one side of the straight line corresponding to the 0 difference between means, ii) inside a difference range of two standard deviations, and iii) in a scale of values on the horizontal axis between 4-6 points (see supplementary material).



	Outdoor High (OH) ° visual arc M(±SD)	Outdoor Low (OL) ° visual arc M(±SD)	Indoor High (IH) ° visual arc M(±SD)	Indoor Low (IL) ° visual arc M(±SD)
Marker1	.32 (.12)	.32 (.12)	.33 (.14)	.34 (.11)
Marker2	.32 (.11)	.33 (.12)	.34 (.12)	.33 (.14)
Marker3	.33 (.12)	.32 (.11)	.32 (.12)	.32 (.12)
Marker4	.33 (.12)	.33 (.10)	.35 (.10)	.32 (.11)
Marker5	.32 (.13)	.32 (.11)	.31 (.12)	.32 (.12)
Marker6	.32 (.12)	.33 (.11)	.34 (.12)	.32 (.12)
Marker7	.31 (.12)	.31 (.12)	.32 (.12)	.33 (.13)
Marker8	.33 (.12)	.31 (.11)	.33 (.12)	.34 (.12)
Marker9	.32(.12)	.34(.12)	.35(.12)	.32(.11)
Marker10	.32(.12)	.33(.11)	.33(.12)	.32(.13)
Marker11	.32(.13)	.33(.13)	.33(.13)	.35(.12)
Marker12	.35(.13)	.34(.12)	.34(.12)	.34(.12)
Marker13	.32(.14)	.32(.12)	.33(.13)	.32(.13)

3.3.2. Consistency between lighting conditions

The repeated ANOVA showed that there were no significant differences in the means of separation distance between gaze location and the center of marker when comparing lighting conditions, either independently of the 13 points of validation ($F(1,3) = 1.46$; $p = 0.293$; $\eta_p^2 = 0.26$) or at each of the points (Table 4 in supplementary material).

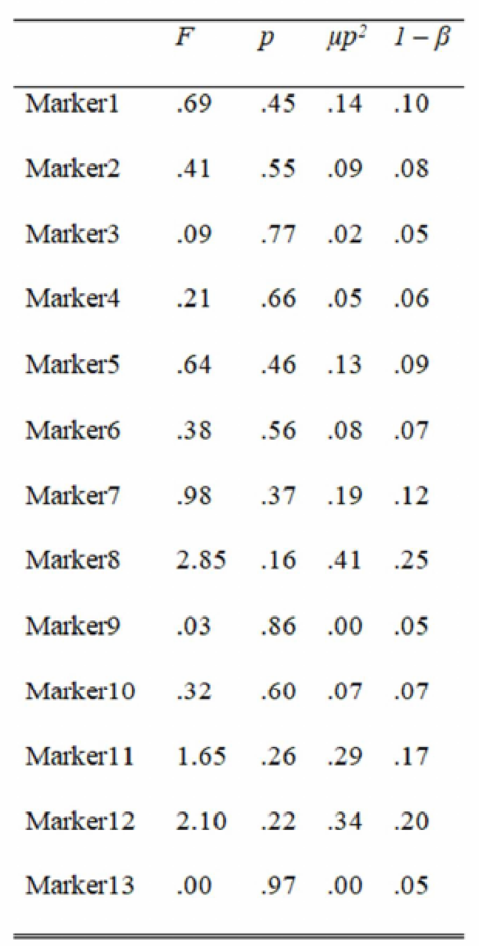


	Pre climbing task test	Post climbing task test
	° visual arc M(±SD)	° visual arc M(±SD)
Marker1	.30 (.12)	.30 (.12)
Marker2	.31 (.12)	.31 (.13)
Marker3	.29 (.11)	.29 (.13)
Marker4	.35 (.12)	.36 (.11)
Marker5	.33 (.12)	.33 (.11)
Marker6	.33 (.12)	.32 (.12)
Marker7	.30 (.12)	.30 (.11)
Marker8	.28 (.12)	.29 (.11)
Marker9	.34 (.12)	.34 (.10)
Marker10	.30 (.12)	.27 (.12)
Marker11	.31 (.10)	.30 (.11)
Marker12	.30 (.12)	.30 (.10)
Marker13	.29 (.12)	.30 (.13)

Bland-Altman graphics showed that the differences in means between pairs of points were: i) distributed randomly to either side of the straight line corresponding to the 0 difference between means, ii) within a difference close to 0, and iii) on the horizontal axis between 4 and 4.5 points (see supplementary material). These differences showed homogeneity since the range was between -0.09 and 0.04, included in the LoA established for each pair of points (see supplementary material).

3.3.3 Consistency between measurements

The repeated ANOVA showed that there were no significant differences in the means of separation distance between gaze location and the center of marker when comparing test application time, either independently of the 13 points of validation ($F(1,3) = 0.07$; $p = 0.801$; $\eta_p^2 = 0.01$) or according to the fixation points (Table 5).



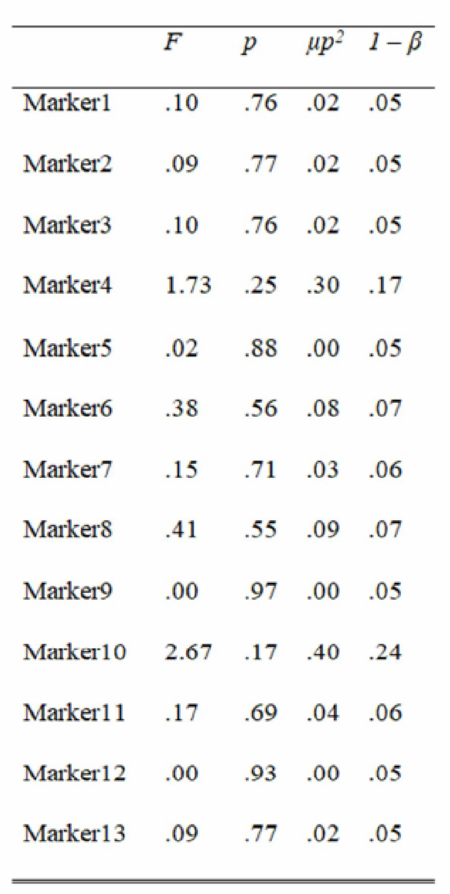
	F	p	μp^2	$1-\beta$
Marker1	.69	.45	.14	.10
Marker2	.41	.55	.09	.08
Marker3	.09	.77	.02	.05
Marker4	.21	.66	.05	.06
Marker5	.64	.46	.13	.09
Marker6	.38	.56	.08	.07
Marker7	.98	.37	.19	.12
Marker8	2.85	.16	.41	.25
Marker9	.03	.86	.00	.05
Marker10	.32	.60	.07	.07
Marker11	1.65	.26	.29	.17
Marker12	2.10	.22	.34	.20
Marker13	.00	.97	.00	.05

Bland-Altman graphics showed that the differences in averages between pairs of points were distributed: i) on one side of the straight line corresponding to the 0 difference between means randomly, ii) within a difference close to 0, and iii) in a scale of values on the horizontal axis between 3.6 and 4.6 points. Complementing these findings, the mean difference between the pre- and post- data during the performance of a climbing task was recorded as 0.16 with a LoA between -0.22 and 0.25 (see supplementary material).

4. Discussion

The low-cost mask-type eye tracker developed in this study demonstrated quality of fixation measurements as evidenced by their accuracy and precision during the validity and reliability tests (e.g., the spatial accuracy reported in all experimental conditions was < 0.5°).

These findings reveal a high level of accuracy, especially when considered that a cone of vision of 1º from 4 m yields a circular area of 21.29 cm^2 (3.49 cm of radius). This level of measurement resolution has been driven by these key questions: i) the logarithm of eye data capture used (RANSAC and the CV functions to improve the detection of the pupil edge), ii) the automatic calibration system selected (the *ImageDraw* function to collect 270 valid calibration points, and controlling the calibration distance), and iii), the procedure followed during the operator-controlled calibration (recovering the first 30 consecutive points by the expert operator from the meta-archive data, and controlling the error of perspective).



	F	*p*	μp^2	$1 - \beta$
Marker1	.10	.76	.02	.05
Marker2	.09	.77	.02	.05
Marker3	.10	.76	.02	.05
Marker4	1.73	.25	.30	.17
Marker5	.02	.88	.00	.05
Marker6	.38	.56	.08	.07
Marker7	.15	.71	.03	.06
Marker8	.41	.55	.09	.07
Marker9	.00	.97	.00	.05
Marker10	2.67	.17	.40	.24
Marker11	.17	.69	.04	.06
Marker12	.00	.93	.00	.05
Marker13	.09	.77	.02	.05

The present device reports accuracy similar to other commercial systems (e.g., ASL, SMI, Tobii) and also shows higher levels of accuracy than other open-source and low-cost systems (e.g., Eye Tribe Tracker; Pupil Labs Headset; Tobii EyeX). In addition to system accuracy, the device is lightweight (approximately 100 g) and wireless. These features, together with the low price (approximately 100€), make it the lightest and cheapest wireless device currently available. In this vein, this device also contained some technical differences in hardware and software design, compared to commercially available eye trackers, to achieve quality criteria for system use and behavioral measurement. To exemplify, the proposed system is portable and wireless to allow analysis of gaze behaviors during natural movements. A band was included to firmly attach the device to the participants´ faces, avoiding the effect of vibrations on the positioning of the eye camera. The device required system calibration for controlling distance and perspective error during eye movement recording, selection of temporal intervals for data collection, and use of a RANSAC algorithm to calculate ocular images. The system also supported fast recognition and recording of the image, online feedback about fixations, and work in dynamic and stable task constraints.

The eye tracker also reported precision based on achieving a moderate ICC level of 0.78[29] in the comparison of 30 participants' measurements. The repeated ANOVA analyses also showed consistency measurements with no significant differences in the accuracy between lighting conditions or test application time.

These results show that the designed eye tracker system is a reliable device for eye movement recordings. The precision is a result of the eye tracker hardware developed (i.e., an integrated mask-type eye tracker that is not displaced relative to the eye when the head moves) and the recording setup introduced (e.g., through the chinrest used during the 13-target grid). This robust device allows head movements during the calibration process (or in natural movements during a climbing task) without decreases in recorded spatial accuracy.

The system is also versatile because the accuracy is not influenced by the lighting environments due to the variable resistor. This specification results in the eye tracker being a suitable device for the on-line tracking of gaze direction independent of stimulus characteristics, while avoiding some stages of processing eye-tracking data[17].

The limitation of the device is that is not suitable for testing saccade movements since the sampling rate configuration is 30 Hz. Despite this limitation, the main focus of the study was to develop an affordable, high-quality device to investigate fixation movements in the sport domain. Its features (low-cost, wireless, comfortable movements, adaptation to varying lighting conditions, robustness, and the possibility to work in open and closed environments) make it a natural perceptual user interface to understand the relation and adaptation of the athletes in their sport tasks[30-31].

The main application of this mask-type eye tracker system is to offer an affordable technological device for high quality recording of eye fixation behaviors to researchers, including investigations of the relation and adaption of humans in many professional performance domains. For example, in medicine, the system can assess how surgeons' gaze behaviors help them perform fine movements during a medical intervention. In transportation, it can be used to ascertain how the perception of relevant road cues helps drivers maintain control of a vehicle. In marketing, fixation data from the eye tracker can provide critical information that will affect how companies design and offer new products and services to increase product sales. In psychology, the differences in decision making processes between people and those with cognitive disorders can be explored with the eye tracker visual fixation data. In education, the eye tracker can investigate how children's visual search strategies enhance their learning during the observation of educational programs and resources.

In future studies, since each type of eye tracking system is sensitive to error[11-12], a comparison could be performed between simultaneous recordings of eye movement data from the current eye tracker system and an existing 'gold standard' system (e.g., a commercial device). This comparison would allow researchers to quantify the reproducibility and variation in performance measurements.

Disclosure statement

No potential conflict of interest was reported by the authors.

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