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Tutorials

Gaze behavior data in the vitrine of human movement science: considerations on eye-tracking technique

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ABBREVIATIONS

AOIs	Areas of interest
DTU	Display/transmission unit

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BACKGROUND: Eyes are the main gateway of visual information input. Moving the eyes is essential to extract visual information from scenes while performing motor actions. This helps to explain motor behavior, especially related to visual attention mechanisms, gaze training and learning, and the relevance of visual information in controlling actions. Thus, collecting data on gaze behavior is important for explaining motor behavior.
AIM: We present the main video-based eye-tracking techniques, briefly describe the anatomy of the eyes, explain the operation of the eye-tracker (eye capture techniques, calibration, and data analysis), and propose interpretations of the main variables that were extracted by the technique. This way we develop considerations (limitations and advantages) on the eye-tracking technique that placed gaze behavior data under the view of human movement science.
INTERPRETATION: Eye-tracking has become an excellent tool to assist in the analysis of human movement through gaze behavior. It is possible to make inferences, mainly from the combination of sensory information, such as visual information, with performance during motor tasks, about perception, cognition, and human behavior during the most diverse day-to-day activities. Eye-tracker systems have been employed in different majors related to motor behavior, such as medicine, commerce, and game development.

KEYWORDS: Eye movement | Vision | Motor behavior

INTRODUCTION

Vision is a striking source of sensory stimuli for humans, as well as other animals. Anatomically, the visual system includes the eyes (which we will emphasize), connecting pathways to the visual cortex and other parts of the brain (e.g., primary visual cortex). Eyes consist of eyelids, pupil, lens, retina, and many other components. All these components are connected to the nervous system and are necessary for visual perception.

The richness of vision comes not only from the functional utilization of the anatomical parts of the visual system but also from eyes movements to achieve the goal of "seeing". While the specific anatomy of human eyes restricts the amount of precise information that enters the nervous system, the ability to move the eyes coordinately allows the capture of relevant visual information from the environment. Therefore, many characteristics of the acquisition of visual information during human movement still challenge researchers who investigate the visual control of actions.

Eye movements are essential to collect accurate visual cues from relevant scene locations, allowing optimal control of human movements in many contexts [1], such as locomotion, balance activities, sports, and driving. Eye movements are particularly essential to guide the movement during obstacle avoidance [2] – obstacle crossing or circumvention –, especially for people with gait impairments [3,4]. Athletes' gaze behavior also reflects perception-based decision-making and execution of motor responses involved in dynamic sports settings. Literature reveals strong evidence that skilled athletes show more efficient patterns of visual search than their less-skilled counterparts [5].

Eye movements are important to explain motor behavior, including questions related to visual attention mechanisms, the relevance of visual information to action control, and learning and gaze behavior training [1]. Understanding the relationship between the object or scene and the observer shows only part of the complexity of actions' timing. More importantly, however, visual information is the basis for humans to guide their actions in order to achieve behavioral goals and synchronize body movements with external events in a perceptual-motor coupling. Despite being constantly used, such relationship is far from simple and trivial. To investigate this topic, it is necessary to identify the association between the most relevant scene characteristics during visual information acquisition and the motor control parameters compatible with this information [6]. Thus, for this research, it seems more important to investigate why humans look at certain visual information when performing complex tasks instead of just knowing where they are looking at [1].

Obtaining spatial-temporal data on eye movements assists in the investigation of most relevant aspects of visual information, perceptual mechanisms, and visual control during motor action. Thus, accurate and reliable eye movement data collection is important to explain and uncover many aspects of human motor behavior. This manuscript is a tutorial for eye-tracking technique use and data analysis. So, in the following sections, we present the main video-based eye-tracker techniques used in human motor behavior and sport science studies. To understand the functioning of eye-trackers, we present a brief description of the human eye anatomy and functional gaze behavior. Two main types of corneal reflection techniques, as well as calibration methods, data analysis, and the potential interpretation of main dependent gaze variables are discussed. Finally, we focus on pointing out limitations and advantages that, in our view, should be taken into account when buying an eye-tracker for empirical work.

HUMAN EYES

The main structures of the human eye include the cornea, sclera, lens, pupil, iris, and retina. Externally, the cornea, sclera, and lens play important roles, while internally, the pupil, iris, and retina are key components. The sclera is the opaque white part of the eyes that provides structural support and prevents the passage of light that could degrade the image on the retina. The lens is a gelatinous structure that can adjust its shape to focus incoming light precisely.

The cornea is a thin tissue that covers the front of the eye and reflects a portion of the light as it travels toward the pupil. The pupil, which is controlled by the iris (eyes' colored part), is the opening that allows light to enter the eye. The size of the pupil is intrinsically linked to various factors such as the amount of light stimulus [7], the autonomous [8] and limbic system [9], and cortical areas [10]. Located at the back of the eye, the retina is a small tissue composed of neurons that play a vital role in visual processing. Within the retina there are two types of photoreceptor cells responsible for converting light into electrical signals: rods and cones. These signals are then transmitted via the optic nerve to the primary visual cortex, where images are interpreted and understood. However, it is important to note that not all information the retina sends to the cortex is processed.

Humans primarily perceive detailed vision through the fovea, which is a small area located in the middle of the macula on the retina. To direct luminous stimuli to the fovea, the eyes need to be moved. The fovea encompasses approximately 1 to 2° of the central retinal area and provides the highest level of acuity or clarity [11]. The fovea consists of specialized photoreceptor cells called cones, which transmit electrical impulses to the brain for interpretation in the presence of ambient light [12]. Cones enable finer and more precise visual discrimination due to their one-to-one relationship with bipolar and ganglion cells within the retina. However, as the stimulus moves toward the periphery, specifically the parafovea, the resolution of the image decreases because of the reduction of the number of cones.

The parafovea covers roughly 10° of the visual arc and is composed of photoreceptors called rods. Rods are more sensitive to light and motion but are unable to provide detailed resolution or color perception due to their many-to-one mapping with the underlying retinal ganglion cells [13]. Due to eyes' structural and functional characteristics, individuals need to continually adjust their eye position by moving their eyes toward the target of interest in order to maintain visual resolution [14]. This dynamic eye movement is crucial for exhibiting well-defined visual behaviors.

GAZE BEHAVIOR

Visual inputs that enable the identification of world characteristics for the brain to process are obtained through the eyes' structure but are heavily influenced by eye movements. Eyes' movements play a crucial role in the interaction between an individual and their environment, contributing to perception and attention [15] mechanisms associated with cognitive and visual processing [16]. In recent years there has been significant growth in the study of gaze behavior, which focuses on examining eye movements [7,17,18]. Gaze behavior encompasses the specific eye movements an individual performs, which are personally relevant to them [19]. These movements' purpose is to seek relevant information and facilitate interaction with the environment. Studying eye movements during everyday tasks such as driving, walking, and crossing obstacles, but also during sports-related skills like decision-making and anticipation provides valuable insights into both visuomotor and visual-cognitive behavior and impairments. Analyzing eye movements in these contexts is an important tool for understanding the intricate relationship between vision, motor actions, and cognitive processes [20,21].

There are five types of gaze behavior:

1) Gaze fixation: it plays a crucial role in human vision by allowing us to stabilize our gaze on specific informative areas in the visual field, primarily using the fovea region for detailed information processing. During gaze fixations, the eyes remain stationary at a point of interest in the environment for a certain time. The duration of gaze fixations can vary, typically ranging from 80 to 1500 ms, depending on factors such as the scene or environment's complexity and the task being performed [22]. In contexts that require high performance, such as sports, medical situations, and other motor tasks, the concept of the "quiet eye" becomes relevant. The quiet eye phenomenon refers to the last fixation on a specific object or location within a visual angle of 3°. This fixation must endure for at least 100 ms and is associated with maintaining visual focus and concentration [5].

2) Smooth pursuit: it is an eye movement characterized by slow and continuous tracking of a moving object, wherein the velocity of the eyes closely matches that of the object being pursued. Human smooth pursuit velocities typically range from 10 to 90 °/s, with eye speed reaching saturation at around 87 °/s, depending on the visual target's [23] characteristics. However, when there are rapid and sudden changes in an object's position within a visual scene, the execution of smooth pursuit movements is impractical. In such situations, it is challenging to extract relevant visual information due to the limitations of smooth pursuit in responding to quick object displacements.

3) Saccades: rapid and sudden eye movements are referred to as saccadic eye movements. These movements are characterized by preprogrammed and ballistic rapid shifts of the eyes, reaching speeds of up to 700 °/s [7]. The primary function of saccades is to rapidly bring a new part of the visual field onto the fovea, the area in the retina responsible for detailed vision. During saccades, the retinal image undergoes a high-velocity displacement that results in a momentary reduction of visual processing. This phenomenon is known as saccadic suppression. As the eyes rapidly move, the visual system experiences a temporary "blinding" effect, leading to poor visual perception during saccades [7].

4) Vergence movements: it occurs when the fovea of each eye aligns with targets located at different distances from the observer. Eye movements are typically conjugate, which means that both eyes move in the same direction. However, when viewing objects at varying distances, convergence movements occur in a deconjugate (or disjunctive) manner. This means that the vision's lines from each eye converge or diverge in relation to the object being observed. The convergence movements are part of the "near reflex triad", which involves three components: 1) convergence; 2) accommodation of the lens - which brings the object into focus, and 3) pupillary constriction - increasing the depth of field and sharpening the image on the retina [24].

5) Vestibulo-ocular movements: they compensate for head movements and stabilize the eyes in relation to the observed environment. These reflex responses play a crucial role in preventing visual images from slipping across the surface of the retina as the head's position changes. Vestibulo-ocular movements can be observed when an object is fixed and the head moves from side to side. In this scenario, the eyes move in the opposite direction to the head movement, ensuring that the object's image remains in the same place on the retina. This compensatory eye movement occurs because the vestibular system detects transient changes in head position and generates rapid corrective eye movements. The sensory information received from the semicircular canals determines the direction of eye movement. It is important to note that the vestibular system is "insensitive" to slow or rotational movements of the head but can effectively counteract fast movements. During continuous rotations without visual cues, such as in the dark or with eyes closed, compensatory eye movements cease after approximately 30 s of rotation. However, when the same test is conducted with visual cues, compensatory eye movements continue due to the activation of the smooth pursuit system, which detects movement in the visual field [24].

Considering the five types of gaze behavior (fixation, pursuit, saccades, vergence, and vestibulo-ocular movements), there is a growing interest in understanding and obtaining information about the first three types—fixation, pursuit, and saccades—, as they relate to the human visual control of actions. These measurement processes have been used for some time, but technology advancements have significantly enhanced several aspects of these processes. As a result, the quality of eye-tracking data and analysis has improved considerably. In this context, we discuss several relevant issues regarding eye-tracking.

DESCRIPTION OF EYE-TRACKING EQUIPMENT

Modern eye-tracking equipment has been specifically designed to track eyes' movements and gather visual information during more complex everyday tasks, mobility activities, and sports activities. Depending on the type of device that is used, the components required for tracking and acquiring gaze data may vary.

For static eye-tracking devices such as video-based systems, the necessary components include a mounting bracket that is positioned directly on a surface (such as monitors or laptop screens) or supported on a tripod. The device is connected to a computer via a USB cable, which is equipped with software for recording, analyzing, and visualizing gaze data. These systems utilize a camera that captures images of both eyes, allowing some tolerance to head movements. On the other hand, mobile eye-tracking devices consist of glasses or a head-mounted unit that includes cameras for tracking the eyes (eye-camera) and capturing the scene (scene camera).

These devices also require a display/transmission unit (DTU). An additional computer is often used to compute and analyze gaze data, although it is not necessary for the data collection process itself. The eye-camera records the eye that is being tracked by reflecting its image from a hot mirror, which is transparent in the visible spectrum but reflective in the near-infrared spectrum. This allows the individual's normal vision to remain unobstructed. On the other hand, the scene-camera records the environment the individual observes and is positioned to capture a straight-ahead view. Both cameras record simultaneously, and data are sent in real-time to the DTU, the computer or both. The additional computer processes the video from both cameras by using specific applications provided by the equipment's manufacturer to calculate the gaze point in the scene image. The processing can be performed in real-time or offline, depending on the equipment and application being used. The frequency of data acquisition also varies depending on the specific device being used. Table 1 below shows some examples of eye tracker manufacturers and models.

Using the aforementioned processing the computer generates a visualization of the gaze point as a cursor, which is overlaid on the scene image. This display may also provide additional information such as pupil diameter and gaze coordinates in relation to the visual field captured by the scene camera. By understanding the underlying eye structures and the several components of eye-tracking equipment, we can gain insight into the workings of eye-tracking techniques (Figure 1).

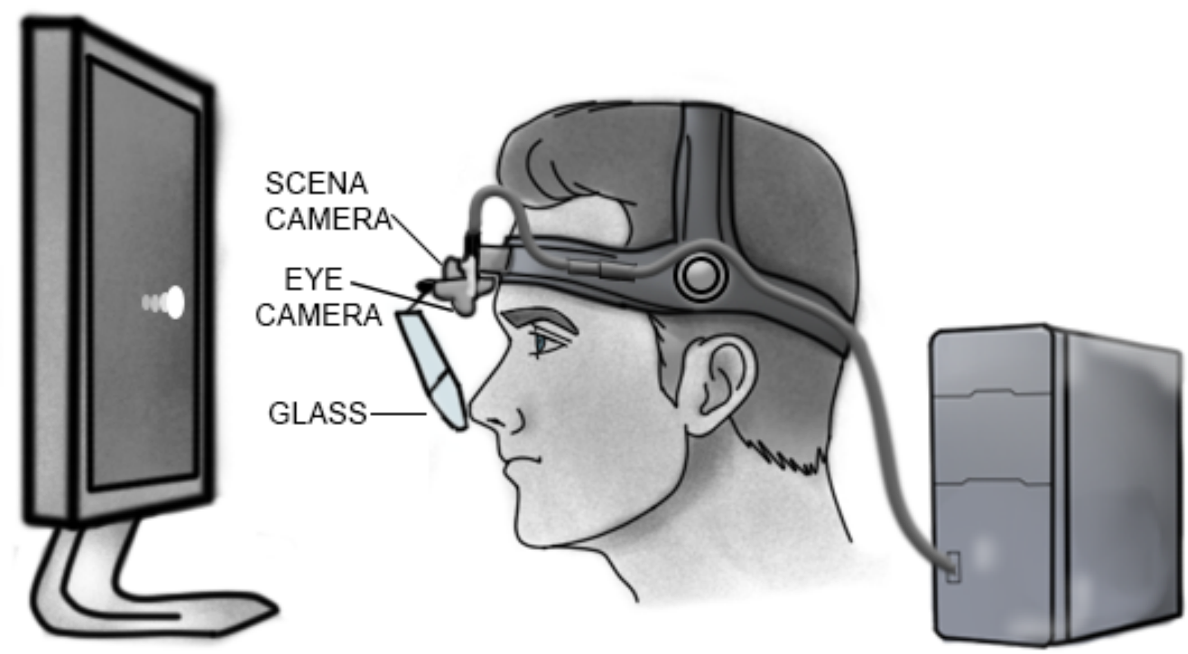

Figure 1. Illustration of the eye-tracking technique (mobile device).

EYE-TRACKING TECHNIQUES

Currently, many techniques are available for tracking and measuring eye movements (Table 1). In the field of human movement science, several techniques are employed to track gaze during human actions. It is important to note that these techniques can be combined to enhance the robustness and accuracy of detecting the fundamental eye features required for accurate eye movement recording.

Corneal reflection in video-based eye-trackers

The corneal reflection method is widely used and popular in eye-tracking studies related to motor behavior. It is also employed by several commercial systems. In this technique, a small source of three near-infrared lights is directed toward the central portion of the cornea and reflected by a mirror. In the case of mobile devices, the reflection of these three lights on the mirror appears as a triangular "spot cluster" in the camera (Figure 2A). The cameras and light source are fixed, and assuming that the eye is a sphere that rotates only around its center, the position of the corneal reflection remains constant [25]. Therefore, the position of the corneal reflection can be a reliable reference point. The eye-tracking system can calculate gaze direction by comparing the vector (angle and distance) between the pupil and one of the pupil reflectors within the spot cluster.

Table 1. Eye-tracker manufacturers, origin, and models' characteristics to acquire visual information data.

Equipment Manufacturer	Origin	Brand	Model	Sampling Rate (Hz)	Static / Mobile (S/M)	Monocular / Binocular (B/M)
EyeTech DS[1]	USA	EyeTech	VT3 mini	40/60/120/200	S	M / B
			VT3 XL	60	S	M / B
Smart Eye AB[2]	Sweden	Smart Eye	Smart Eye Pro	60	S	M
			Aurora	60/120/250	S	B
			XO	30/120	S	B
			AI-X	60	S	B
Gazepoint[3]	Canada	Gazepoint	GP3	60	S	B
			GP3 HD	150	S	B
Pupil Labs[4]	Germany	Pupil Labs	Pupil Core	200	M	B
Argus Science[5]	USA	Argus Science	ETVision System	180	M	M
Tobii Technology AB[6]	Sweden	Tobii	Pro Glasses 3	50/100	M	B
			Pro Spectrum	60/120/150/300/600/1200	S	B
			Pro Fusion	30/60/120/250	S	B
			Pro Spark	30/60	S	B
			Pro Nano	60	S	B
SR Research[7]	Canada	Eyelink	Eyelink II	500	M	B
			Eyelink 1000 Plus	2000	S	B
ISCAN[8]	USA	ISCAN	ETL100H	60	M	M
			ETL100R / 101R	60	S	M
			ETL200	120/240	S	M
			ETL300	60	S	B
			ETL400	60	S	M / B
			ETL500A	60	M	M
			ETL500B	60	M	B
Ergoneers GmbH[9]	Germany	Dikabilis	Professional Glasses	60	M	B
Scottsdale[10]	USA	Arrington Research Inc.	Eye-Frame SceneCamera BSU07/BSU07-220/BSU07-400	30/60/220/400	M	B
			Head Fixed BCU902/BCU02/BCU400/ MCU902/MCU02/MCU400	90/220/400	S	M / B

[1] https://blog.eyetechds.com/
[2] https://smarteye.se/solutions/products/
[3] https://www.gazept.com/shop/
[4] https://pupil-labs.com/products/core/
[5] http://www.argusscience.com/ETVision.html
[6] https://www.tobii.com/products/
[7] https://www.sr-research.com/
[8] http://iscaninc.com/
[9] https://www.jalimedical.com/dikablis-glasses-eye-tracker.php
[10] http://www.arringtonresearch.com/ViewPoint_EyeTracker_Catalog.pdf

In real-time, a computer identifies the relative position of the pupil and corneal reflection based on the contrasting features of these eye structures. The centroids of the pupil and corneal reflection are calculated, and their horizontal and vertical coordinates (in pixels) are used to determine the line of sight relative to the optical system of the eye-tracking equipment [26]. The angle of the visual axis is then calculated by tracking the relative position of the pupil center and a "patch" of light reflected from the cornea, within 1 degree of the visual angle, through a calibration procedure. As a result of this process, a cursor is generated and added to each frame of the scene camera image. This cursor indicates the specific location where the person is looking at that particular moment (Figure 2B).

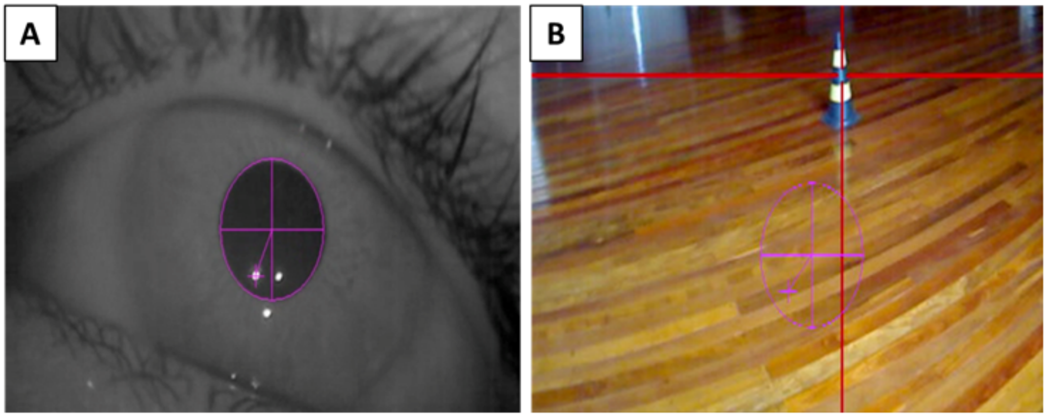

Figure 2. Images from eye and scene cameras of an eye tracker during the view of a static object. The spot cluster is shown in the left panel (A), where the pupil is also marked (purple round line). In the right panel (B), the cursor (red crossed lines) is combined with the environment image and indicates the location at which the individual is gazing in the scene after calibration.

Bright pupil

The bright pupil technique in eye-tracking is achieved by illuminating the eye with an infrared light source that is positioned on or near the camera axis. When this infrared light falls on the retina, it causes the pupil to appear brighter compared to the surrounding iris. This is because the reflective properties of the retina result in a higher reflection of the incident light, similar to the "red-eye" effect observed in flash photography [27].

In the bright pupil technique, the camera captures an image of the eye, and the pupil is identified as the region of higher brightness due to the reflection of the infrared light. This technique allows the detection of the pupil with improved contrast against the iris, facilitating accurate tracking of eye movements. With this technique, the retina can reflect 90% of the incident light with a wavelength of 850 nm. An example of bright pupil detection can be seen in Figure 3A.

Dark pupil

The dark pupil technique is used to enhance the detection of the pupil by making it the darkest region in the image. This technique involves illuminating the eye with a near-infrared light source that is positioned off-axis along a converging path with the camera's image axis. The light source emits near-infrared light with a specific wavelength, typically around 880 nm.

To ensure that only the desired near-infrared light reaches the eye camera, a narrow bandpass filter is employed. This filter allows light centered around the 880 nm wavelength to pass through while blocking other wavelengths, including ambient light sources. This prevents and reduces possible interference from external light sources (e.g., the sun) to corneal reflection and pupil detection. The equipment employs three near-infrared LEDs, forming a triad of corneal reflections, as well as the spot cluster. The eye-tracking equipment detects this contrast and identifies the darkest region as the pupil. This technique improves the accuracy of pupil detection, even in challenging lighting conditions. By employing a triad of corneal reflections and a spot cluster, the equipment further reduces the likelihood of attaching to false corneal reflections caused by ambient lights, which could lead to inaccurate gaze output. An example of dark pupil detection can be seen in Figure 3B.

CALIBRATION METHODS

An important issue related to the use of any eye-tracking system is the calibration procedure. Calibration is needed to provide the spatial references of the three-dimensional environment for the software system. The calibration procedure allows accurate detection of the pupil/corneal reflection and, consequently, precise gaze positioning. It is necessary because the shape of the eye differs for each person, and thus, it must be considered to ensure accurate eye position and orientation. The calibration of eye-tracking equipment involves storing and analyzing enough points (data) simply and efficiently. This process is performed by indicating "reference points" or calibration points that participants need to look at, and evaluators indicate the corresponding locations of these points on the screen to the software. Through these procedures, synchronization between where the person is looking and what is being measured by the equipment is achieved, establishing a mapping model.

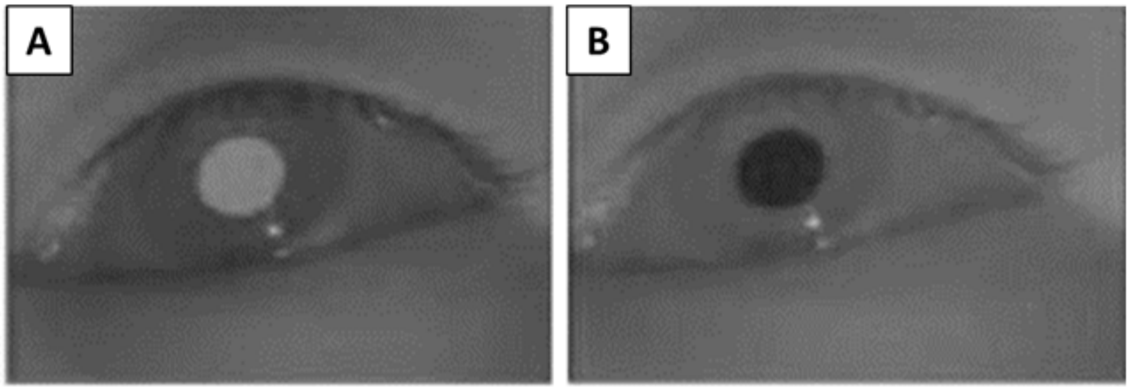

Figure 3. The (A) Bright and (B) Dark techniques for pupil detection are employed to track eye movements. (Adapted from Zhai et. al.[47]).

Tracking individuals' eye movements with traditional eye trackers can be costly and demanding for the participants. To address this, a point-based calibration method has been developed to make eye-tracking applications more accessible and cost-effective [28]. This method involves estimating the differences in shape and model of the eyeball while the subject focuses on a calibration marker. The calibration parameters can compensate for some measurement errors, known as residual error [28], by calculating a correction coefficient.

There are several standardized procedures for eye-tracker calibration, and the main difference is the number of calibration points that are used. Whereas some eye-tracking systems require a 1- or 3-point calibration procedure, the most common approach involves presenting a square grid consisting of 9 to 25 points arranged in a 3x3 (Figure 4) to 5x5 grid pattern. Increasing the number of calibration points can enhance the accuracy of the eye mapping model by providing more input data [29]. However, complex calibration procedures can be inconvenient for participants, which leads to potential drawbacks [30]. Although it is possible to track gaze by using just one calibration point, which speeds up the process and reduces research costs, currently no existing study demonstrates the reliability of this technique.

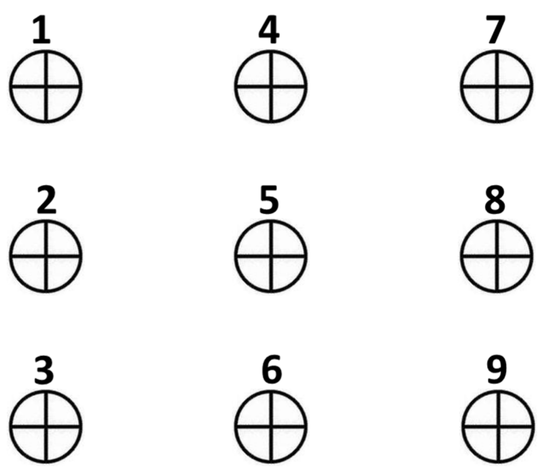

Figure 4. Example of a nine-point calibration method presented in a square 3 x 3 grid. In this method, participants are instructed to look at the points in numerical order based on the evaluator's command.

DATA ANALYSIS AND PARAMETERS CALCULATION

Eye movement data can serve several purposes, with the primary application being the estimation of gaze points to determine where a person is looking. Eye-tracking equipment records eye movements and provides synchronized and calibrated information about the eye and gaze points [30]. The raw data captured by eye trackers include the horizontal and vertical coordinates of the eye position over time. Figure 5 illustrates example time series of eye movement data, with the top panels displaying the horizontal coordinates and the bottom panels displaying the vertical coordinates. The data correspond to an adult in an upright standing position, focusing on a target.

During the gaze fixation condition (left panels), the individual is instructed to maintain fixation on the target throughout the trial. In the horizontal guided-eye condition (right panels), the target appears on the right side of a monitor, disappears, and reappears on the monitor's left side at a frequency of 0.5 Hz. The individual is instructed to fixate on the target accordingly.

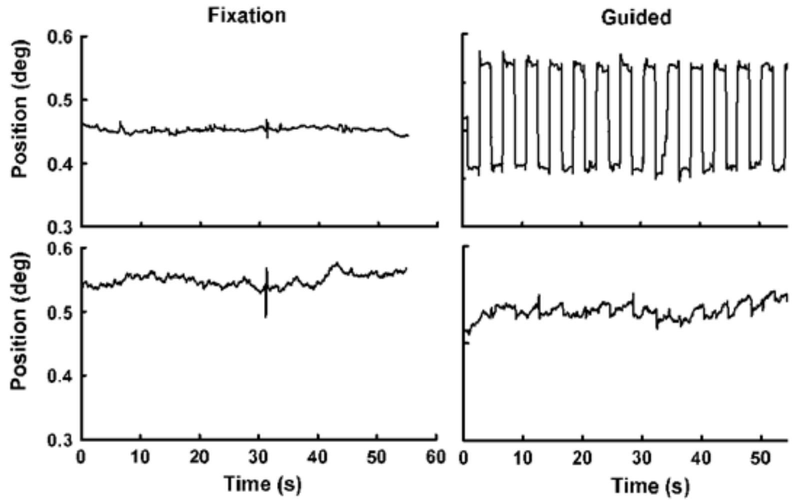

Figure 5. Exemplar time series of a person's eye movements in the fixation (left panels) and guided (right panels) conditions in the horizontal (top panels) and vertical (bottom panels) directions.

The position of the eye corresponds to the direction of the viewer's gaze and is closely associated with the location of visual attention [7,26,31]. Whether we fixate on an object or guide our eyes to specific targets, eye-tracking provides valuable insights. This approach can be applied in various situations and conditions. For example, Figure 6 illustrates the monocular eye position along with the horizontal and vertical coordinates while a person reads a text with three lines. The figure shows gaze fixations that are represented by large spots and saccades that are represented by small spots as the person progresses through the words in the text, fixating on individual words and moving their eyes from left to right along the text line.

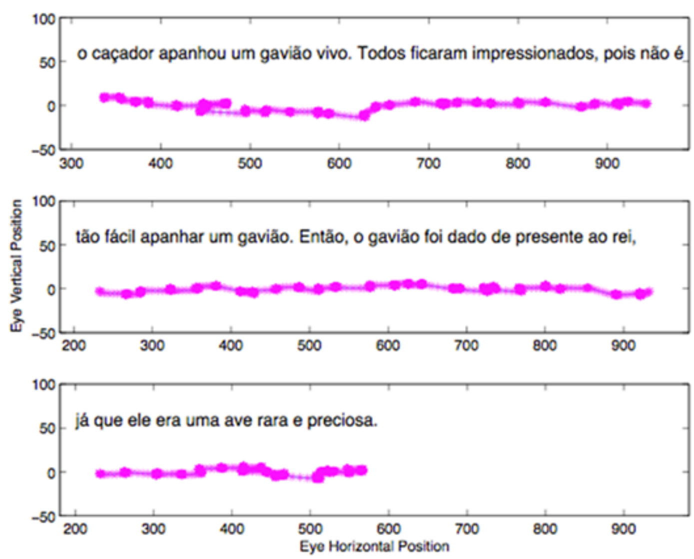

Figure 6. Exemplar of approximate eye positioning, vertical and horizontal coordinates as a person reads the respective text. Note: The text is in Portuguese because it was the original language during reading.

The spatial-temporal coordinates of gaze location are crucial for representing eye behavior. However, to fully characterize eye movement behavior, these coordinates need to be processed by using quantitative and qualitative methods. Linear approaches such as dwell-time fixation detection and velocity-based saccade detection have been widely used to analyze eye movements [26]. In addition, non-linear methods have emerged as alternative approaches for eye movement analysis [31].

Linear parameters

The dwell-time fixation approach, also known as the dispersion-based approach, involves identifying a fixation when the eye position, which is represented by the intersection point of vertical and horizontal gaze coordinates, remains within a specific spatial threshold (e.g., 1 degree of visual angle) for a minimum duration (e.g., 100 ms as suggested by Vickers [5]). This method relies on detecting spatial stability in the eye movement signal, assuming low variability in eye position, and setting a time window that defines the duration required to meet fixation criteria.

Velocity-based saccade detection is another conventional method that is used to analyze eye movements. In this approach, the eye velocity within a specific sample window is compared to a predetermined velocity threshold, such as 300°/s. Saccades are identified when the eye velocity exceeds the threshold, while the intervals between saccades are considered as gaze fixations [26]. The selection of an appropriate velocity threshold is task-dependent and usually determined through empirical calibration. Previous research has demonstrated that a detection threshold of 130 °/s can be chosen for saccade detection via eye velocity [26]. We should note that higher velocity thresholds need a higher sampling rate during data collection to accurately capture rapid eye movements.

In eye movement research, several commonly reported measures are used to analyze eye movements. These measures include [17,32]:

- Total number of fixations: this measure represents the overall count of all fixations an individual makes during a task or observation. It indicates the frequency of shifts in visual attention.

- Mean fixation duration: this measure calculates the average duration of all fixations recorded. It reflects the average amount of time an individual fixates on a particular location or stimulus. Mean fixation duration is often used as an indicator of cognitive processing demands, with longer durations suggesting more extensive processing. It has been considered an indication of time spent processing the visual stimuli from the environment [33] and represents the most sensitive measurement of processing demand.

- Horizontal and vertical variance of fixation location: these measures assess the variability or dispersion of gaze positions in the horizontal and vertical dimensions. They quantify the extent to which fixations are distributed across the visual field. Higher variance values indicate greater variability in eye movement patterns.

- Total dwell time: it refers to the cumulative time that gaze coordinates remain within specific areas of interest (AOIs). AOIs are task-specific regions defined in the viewing plane, typically based on the visual scene captured by the eye tracker (as shown in Figure 7). Researchers can analyze the fixation behavior and the distribution of visual attention by calculating the total dwell time in each relevant part of the visual scene. Total fixation duration is a dependent variable that provides an overall representation of the fixations pattern over time. It captures the duration of all fixations recorded during a task or observation and helps us to understand the temporal aspects of gaze behavior. Horizontal and vertical variance in fixation location indicates the spread of gaze positions across the visual field33. These measures quantify the extent to which fixations are dispersed or concentrated in different areas. Higher variance values suggest a greater visual exploration and a wider distribution of fixations. To calculate variance, we determine the square root of the standard deviations of fixation positions in both the horizontal and vertical axes. This analysis provides insights into the variability and spatial distribution of eye movements. It is important to remark that while these measures offer a general understanding of eye movements, they represent a descriptive analysis and may not capture the dynamic visual scanning patterns employed during more complex or dynamic tasks.

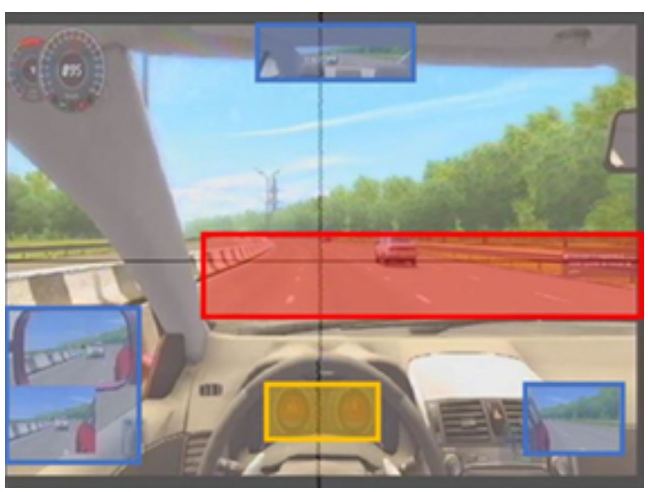

Figure 7. Areas of Interest (AOIs) lane (red), speedometer (yellow), and rear-view mirrors (blue) during the simulated car-driving experiment. The black cursor represents the eye position. (Adapted from Gotardi et. al.[17])

Pupil diameter is another valuable measure that eye-tracking systems provide. It is an indicator of cognitive workload and mental effort, as pupil diameter tends to increase with increased cognitive demand. Gaze patterns and pupil diameter can be systematically analyzed together to gain insights into cognitive processes. One method used to analyze the relationship between fixation and pupillary response is the fixation-aligned pupillary response averaging, as it was developed by Klingner [34] and applied by Carizio et al. [35] in their study on driving and phone conversation (Figure 8). In this study, participants were engaged in a simulated car driving task while talking on the phone, and eye-tracking data, including pupil diameter, were recorded. For each trial, which lasted 60 s, a variable number of fixations was identified. Curves of pupil diameter data were selected based on fixation onset, with each epoch starting 500 ms before fixation onset and ending 500 ms after it. These curves allowed the calculation of an average curve for each trial, along with standard error values at each data point. The number of curves in each condition corresponded to the number of fixations observed in that condition.

To analyze pupillary response, a baseline was established by calculating the average pupil diameter over the 500 ms period before fixation onset. This baseline value was then subtracted from all values in the respective curve. The average procedure also involved the estimation of the amount of noise by calculating a plus/minus average using the same curves. The purpose of this averaging technique was to preserve the task-evoked pupillary response signal while reducing the influence of signal components not temporally correlated with gaze events, referred to as noise. For more detailed information on the methodology and analysis, please refer to the study by Carizio et al. [35].

Non-linear parameters

Saccades and gaze fixation are important mechanisms that enable efficient visual scanning of the environment and are tailored to the task's specific goals. These eye movements allow individuals to direct their attention to task-relevant information. Whereas linear measures such as fixations and saccades provide valuable insights into eye movement behavior, non-linear variables such as visual entropy offer a more comprehensive assessment of the patterns of visual scan paths.

The visual scanning strategy, which is characterized by the eyes' coordinated movement to gather task-relevant information, is not solely determined by the environmental stimuli itself, such as salient objects or optical flow. It is also influenced by "top-down" commands that originate from executive regions of the brain. These commands are associated with task instructions, attentional control, and the perceiver's intentions. In other words, it is not only the visual characteristics of the environment that influences the scanning pattern, but also cognitive factors and the individual's goals and intentions. This integration of bottom-up sensory inputs and top-down cognitive processes contributes to the adaptive nature of eye movements during visual exploration.

The visual entropy approach is an emerging method for quantifying eye movement behavior, but currently limited research [31,36] supports its application. Entropy is a measure that captures the uncertainty or complexity of a system by considering the probabilities of different events occurring. In the context of eye movements, visual entropy is based on Information Theory [37], which suggests that the complexity of a system is related to the amount of information required to describe it. Saccadic eye movements, being a stochastic process, involve interrelated probabilities and do not follow an equiprobable state-space system. Therefore, the analysis of visual entropy takes into account the non-equiprobable nature of saccadic eye movements. The key idea is that each fixation represents a transition from one portion of the visual scene (known as Area of Interest or AOI) to another, forming a network of pathways across the horizontal and vertical planes. A conditional transition-probability matrix is used to track the frequency of fixation transitions between AOIs in order to calculate visual entropy. This transition frequency matrix is then transformed into a Markov chain [36], considering the dwell time in each AOI. The visual entropy is computed using the following specific equation:

$$H(R) = -\sum_{r_i} p\,(r_i) log_2\, p(r_i), r_i > 0$$

where R is a normalized transition matrix and ri are the cell values of that matrix with probabilities p(ri).

Visual entropy refers to the tendency of fixation patterns to exhibit randomness. When visual entropy is high (Figure 8), observers tend to distribute their gaze evenly across different AOIs and transition between AOIs with similar frequencies. On the other hand, decreased visual entropy suggests more ordered fixation patterns, indicating a narrower focus of attention on a limited set of potential fixation points, resulting in lower transition probabilities between AOIs. In other words, attention focuses on a narrower range of potential fixation points (i.e., the possibility of transition) with lower visual entropy. It has been suggested that high visual entropy may indicate a propensity for exploration and curiosity, whereas lower visual entropy may reflect a more focused and directed visual exploration [38]. Additionally, higher gaze transition entropy can indicate increased top-down influence on eye movements, which suggests that cognitive factors and task instructions play a stronger role in guiding gaze behavior [31].

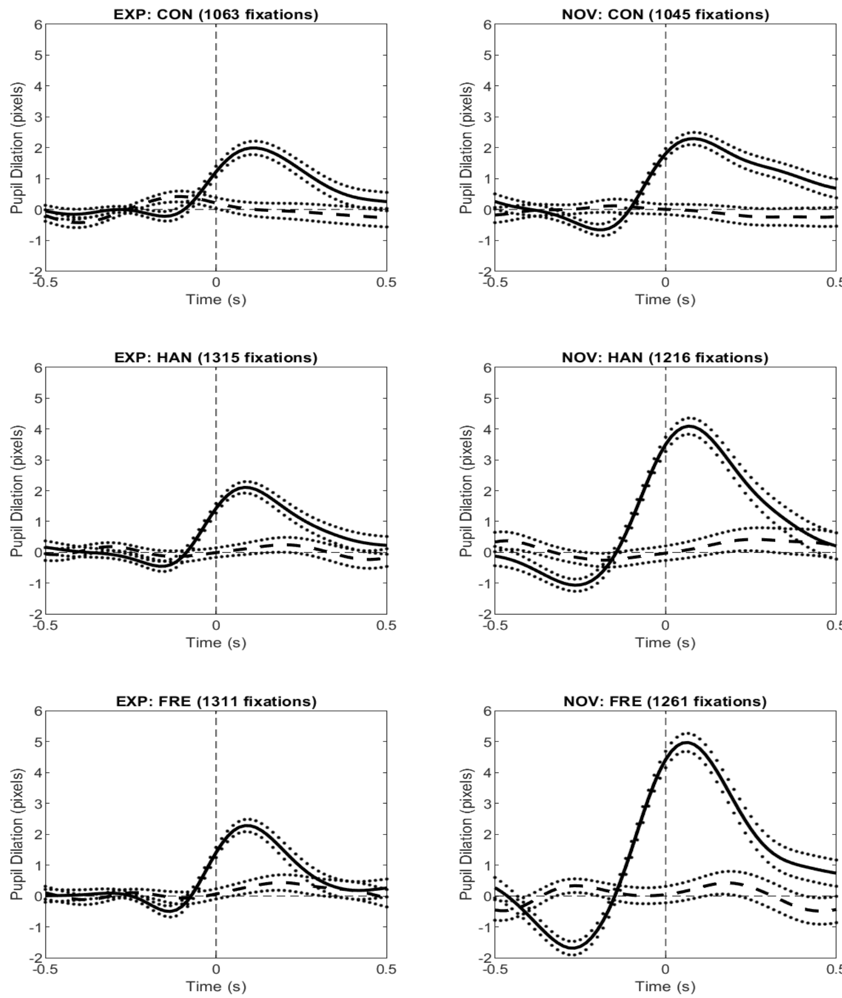

Figure 8. Pupil dilation (pixels) mean (solid line) and noise (dashed line) [± standard error (dots)] of experienced (EXP) and novice (NOV) groups during control (CON), handheld (HAN), and hands-free (FRE) conditions. Zero time equals fixation onset is a characteristic used to temporally align all curves represented (equal to the number of fixations on the top of each plot). (Adapted from Carízio et. al. [35]).

CHOICE OF EQUIPMENT

Technology advancement has led to notable progress in eye-tracking measurements. Traditional static devices with high sampling rates (ranging from 200 to 1000 Hz) have been replaced by mobile devices that prioritize mobility but sacrifice acquisition frequency (ranging from 30 to 120 Hz) [39]. The equipment sampling rate directly impacts instrument validity and data reliability. During saccades, eyes move very fast, and correct detection of these movements depends on a sufficient amount of sampling.

During rapid eye movements known as saccades, it is crucial to have a sufficient sampling rate for accurate detection. Studies have recommended a temporal resolution of at least 50 Hz for reliable saccade detection by using velocity-based algorithms [39]. Furthermore, other research has shown that an acquisition frequency of at least 120 Hz is necessary to improve the detection rate of saccades [40]. Additionally, a minimum of 200 Hz is required [39] to enhance the measurement accuracy of saccade duration. Therefore, mobile equipment with lower temporal resolution, typically up to 60 Hz, may not provide sufficient reliability in both the detection and measurement of saccade durations. On the other hand, both video- and infrared-based eye trackers can provide comprehensive recording of spatiotemporal features of movements during everyday tasks.

Considering the task's specific requirements and other relevant factors is crucial when selecting an eye-tracking system. Different types of tasks may need different approaches to ensure optimal data collection and analysis. For example, a mobile eye-tracking system, which allows the participant to move freely within the data collection environment, is recommended for tasks involving sports or dynamic activities. The mobile system provides valuable visual information even at a lower sampling frequency. Despite the potential sacrifice in sampling rate, the mobile system ensures the capture of relevant eye movement data related to the task's specific demands. On the other hand, if the task primarily involves stationary or minimal head movement, such as reading, viewing images, or watching videos, a static gaze tracker is often the preferred choice. Static eye-tracking systems offer higher accuracy in analyzing eye movements as they provide a stable and controlled setup where the participant's head movements are limited. This enhances the precision of the analysis, particularly for tasks that require precise fixation and attention to specific visual stimuli.

LIMITATIONS

The eye-tracker system is undoubtedly a valuable tool, however, it is essential to acknowledge certain limitations associated with its use: i) cost: in developing countries, the cost of eye-tracking equipment is often significantly high, exceeding US$ 25,000. This cost encompasses both the device itself and the accompanying software required for data acquisition and processing. While attempts have been made to develop homemade alternatives, the validity and reliability of the data obtained from such alternatives often remain questionable [41]; ii) eyes shape: variations in eye shape, such as drooping eyelids, can obstruct the pupil and hinder accurate eye tracking. In such cases, tracking the movement of the eyes becomes challenging [42]; iii) calibration process: collecting eye-tracking data in real-world or in-situ environments presents difficulties, particularly when dealing with highly luminous surroundings [43]. Calibration in such environments becomes arduous, and maintaining the accuracy of the calibration over time can be a challenge, requiring constant revision, correction, and recalibration [44]; iv) individual habits or conditions: factors such as excessive caffeine consumption [45] or high levels of anxiety [46] can affect pupil diameter, making it difficult to detect and track pupil movements accurately.

Considering these limitations, researchers who use eye-tracking systems must carefully address these challenges and consider potential sources of error to ensure data accuracy and reliability. In addition, continuous technology advancements and ongoing research efforts aim to mitigate these limitations and improve the overall usability and accessibility of eye-tracking systems.

FINAL REMARKS

Eye-tracking has emerged as a valuable tool for studying motor control and human movement performance by analyzing gaze behavior. With the combination of visual information and motor task performance, researchers can gain insights into perception-action processes, cognition, and human behavior. The assessment of eye-tracking provides valuable information on attention, interest, and arousal, which in turn affect motor performance in several activities, including locomotion, motor function, and sports tasks.

Eye-tracking systems have found applications in diverse fields such as medicine, commerce, and game development, enhancing our understanding of motor behavior. Researchers in areas like motor behavior and neuroscience, both in typical populations and those with behavioral or motor disorders, are increasingly utilizing eye-tracking techniques. As eye-tracking technologies and other motion measuring systems continue to advance and gain popularity, future studies should explore their application in real-world situations and diverse populations to enhance our understanding of motor behavior in daily activities and sports performance. Moreover, the potential of eye-tracking to aid the diagnosis and treatment of movement disorders should be further investigated. By leveraging the capabilities of eye-tracking technology, researchers can improve diagnostics and therapeutic approaches for individuals with movement-related conditions.

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