A Brief History of Eye Movement Research

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Abstract

This chapter will provide a brief overview of the rich and fascinating history underpinning contemporary eye-movement research. Starting with the early work by Kepler and the largely observational investigations of eye-movements conducted by others, we will cover the development of eye-movement research in terms of the machinery used for early investigations, such as crude measurements using plaster of Paris, as well as set out some of the first instances of phenomena which are still keeping scientists occupied today. Hopefully, by the end of this chapter, you will appreciate the broad history behind some of the topics covered throughout the rest of this book.

Background

Human vision first begins with the eye, at the point when light hits the retina and is then transferred into the brain at speeds estimated to be around 875,000 bits per second [1] - the same speed as the average internet connection, in order for it to be processed by various brain regions associated with higher and lower order processing. The eye itself is a wonderfully complex optical device, which has inspired the design of many of the lenses used in today's endeavours such as photography or scientific investigation. Eye movements are considered the most frequent of all human movements [2]. This calculated, frenetic movement developed as a consequence of the enormous amount of visual information available to an organism. Rather than process the entirety of the information at our disposal, only small portions of the visual world are attended in rapid sequence [3]. The human eye monitors a visual field of around 200°, but detailed information is received from only around 2° [4]. This richly detailed region, known as the fovea, jerks around at speeds of up to 500° per second, during which the sensitivity of this area drops to near blindness levels [5][6].

Eye movements are therefore fundamental to the operation of the visual system. Yet, the eye is more than a simple data-collection device; it is also able to provide insights into behaviour due to providing rich metrics, which is why it is often referred to as the window to the soul. Given that many cognitive processes begin here, it is unsurprising that there has been a rich scientific history of eye-tracking.

17th Century

The history of eye-tracking research is intimately tied to the history of research on the eye itself. Indeed, many of the questions about the mechanisms and the operations of the eye originate back to at least the 17th century. This period was when our knowledge of vision and vision research benefited greatly from an increased understanding of ocular optics and ocular anatomy. Some of the earliest work on vision was conducted by Johannes Kepler (1571-1630). Kepler was a German Astronomer and Astrologist who is considered to be the founder of modern optics. Kepler's discussion of artificial observation (the use of instruments to observe the eye as opposed to direct observation) caused the human observer to fall away from the field of optics and led to a move towards the use of instruments in observation. In his seminal book "*Ad Vitellionem Paralipomena, Quibus Astronomiae Pars Optica Traditur*" (1604), Kepler provided an analysis of human vision, and this has been the basis for further advances in the knowledge of the structure and function of the eye [7]. Kepler compared the function of the eye to that of a camera and speculated that there must be a mechanism, similar to which exists within a camera, which allows the lens of the eye to change shape thus enabling the eye to focus on objects at different distances [8]. Although at the time he was unsure of what this mechanism might be. However, light was now thought of as the agent of vision, rather than just a required condition for vision to occur. This shift in explanation of vision reformulated the field of optics.

The earliest examples of eye-tracking could be considered to be observational studies. Scheiner (1573-1650) conducted a series of experiments in which he demonstrated the reaction of the pupil to different stimuli [9]. Building on the work of Kepler, Scheiner stipulated that if you stand a person in bright sunlight and observe their pupil, you will see that the pupil constricts, decreasing in size. Whereas if you move them into a darker area with less light, the pupil will dilate, becoming larger again, demonstrating the reactivity of the pupil to light. Scheiner was also instrumental in the understanding of accommodation, by the demonstration of the narrowing of the pupil when a small object such as the pinhead of a needle is moved close to the eye and then away again [10]. Not only did this build upon the work of Kepler, but his work was crucial to the understanding of accommodation and was the basis for all future work on this.

Although Kepler's optics clearly improved our ability to understand optical phenomena, it was not widely embraced or indeed appreciated at the time. Instead, the traditional teleological view of optics was preferred, owing to the influence religion and the church still held over scientific discovery around this period. One researcher who did not shy away from this paradigm shift was Descartes (1596 – 1650), who used Kepler's optics to explain the perception of rainbows and discovered the law of refraction, describing them as the refraction of the "rays of light against those drops, and from there toward our eyes" [11]. Despite using Kepler's optics, Descartes view was rooted in traditional optics in both the instrumentation used and the privilege attributed to the eyes. However, it was soon apparent that the angles of refraction did not refer specifically to the eye, and that just as Kepler has stated previously, the rays of light fall on all screens in the same way, including the eyes. By doing so, Descartes was able to construct a physical-experimental model of refraction and projection with a prism, with the eye being completely incidental to the phenomena, using this methodology to directly investigate colours [10], and furthering understanding of the processes of the eye.

18th Century

The 18th century marked the beginning of the experimental exploration of vision. Religion began to exert less of an influence on the scientific study of the eye, and as such there was a shift towards the objective measurement of eye movements.

Afterimages, defined as the lasting visual sensation that persists after the stimulus has disappeared [12], were commonly used during this period to investigate vertigo, accommodation, and binocular vision.

Porterfield (1696-1771), an esteemed Scottish physician of the time and the first to use the term “accommodation” when referring to the ability of the eye to focus on objects at different distances [13]. Porterfield demonstrated the involvement of the crystalline lens in accommodation by observing an aphakic patient - an individual who does not have a lens in their eye - and identified that accommodation did not occur in this individual [14]. Porterfield also devised the optometer, which could be used to measure the near and far points of vision to provide prescriptions for eyeglasses and for measuring the refractive error of the eye. This instrument became widely used up until the mid 20th century when more modern instruments were developed to replace this [15].

The process of accommodation was further investigated by the American William Charles Wells (1757-1817). In opposition to Porterfield, Wells argued that the perception of visual distance is learned rather than innate ability, as argued by Porterfield [14]. Wells conducted a series of experiments in the 1790s, and in an essay published in 1792, put forward three propositions which explained single and double vision, in that something looked at directly using both eyes would appear as a single object, but other objects in the background that were not being focused on would appear to move to the left or right or be seen twice [16].

Wells mainly tested these propositions using pieces of coloured string and wire for the stimuli [17], however, his predictions and tests were not fully appreciated until much later on. Wells used afterimages and their apparent stability or motion as an index of whether the eyes moved as a result of voluntary or involuntary muscular activity, a method that was then widely used by ensuing researchers to investigate the effects of vertigo on eye movements and to investigate whether the eyes continue to move after body rotation has stopped. Further observations on patients who had previously suffered from catarrh and complained of pressure in the forehead and a loss of ability to move the eyelid. This then led to the patient’s pupils becoming dilated permanently. After observing these two patients, Wells discovered that they lacked the ability to accommodate, furthering understanding of the involvement of pupil dilation in accommodation [18].

In a similar vein, throughout this period of time, the medical student Thomas Young (1773-1829) was also working on accommodation, specifically the mechanisms involved in this process. Dismissing most of the theories of the time, Young believed that the lens was muscular, and accommodation occurred via changes in the curvature of the crystalline lens as this, in his mind, was the most logical explanation [19]. Young continued to investigate the mechanisms of the eye into the 19th century, which will be discussed later in this chapter.

19th Century

By the 19th century, scientific understanding of the structure and function of the eye was better recognised, consequently, the focus of eye-movement research shifted to using more precise instruments to understand eye-movements. During this time, vertigo was still a particular focus as many researchers attempted to figure out the mechanisms and conditions which could induce this false sensation of movement. Crude eye recording equipment was developed and used to more accurately and objectively measure eye movements, many of which involved something being physically attached to the eye. These devices would be the basis on which modern eye-tracking equipment was developed. During this century, great leaps in eye-tracking methods and understanding would be made informing much of the methodology still used today.

As mentioned previously, at the turn of the 19th century, Young was working with the hypothesis that the crystalline lens was muscular. He examined the arguments against this hypothesis [20] in his paper “The Baerian Lecture. On the Mechanisms of the Eye”. The main theme of the paper was the ability of the eye to accommodate itself to see objects at different distances, arguing that accommodation occurred as a result of changes to the lens, and not due to changes in the length of the cornea or changes in axial length.

Vertigo was of particular interest around this time, with many researchers attempting to determine the mechanisms by which it occurred. Purkinje (1787-1869) is considered to be a pioneer of modern experimental physiology who made significant contributions to various scientific fields [21]. In terms of contribution to eye movement research, Purkinje conducted a series of observations that allowed him to pin down the conditions necessary to induce vertigo. In a series of experiments in which subjects were sat on a rotating chair in order to induce vertigo, Purkinje observed that vertigo is “a consequence of the conflict between unconscious involuntary muscular actions and voluntary conscious ones in the opposite direction” (Purkinje, 1827, p.297). These observations are now referred to as Purkinje’s Law of Vertigo (1827) [22]. Purkinje-Samson images, which describe the phenomenon of seeing specular reflections of a light source when in dark conditions, came about as a result of his experimentation. This discovery has a variety of applications, including the development of modern eye-tracking systems used to measure eye position [21].

Purkinje’s own interpretation of vertigo was later influenced by the work of Flourens (1794-1867) [21]. He sectioned the semi-circular canals of pigeons and demonstrated that the destruction of a particular semi-circular canal elicits eye movements in the same plane. It also elicits disturbances of posture and equilibrium, in a similar way to vertigo [23]. Purkinje (1826) was intrigued by Flourens’ work and saw the relevance of it in his own work [21]. Work on the sectioning of semi-circular canals carried on throughout the 19th century by researchers such as Breuer (1874), Mach (1875), and Crum Brown (1878) [24].

Despite the use of afterimages by many researchers of the time, Helmholtz (1821-1894) dismissed their use due to their poor level of accuracy. For the use of afterimages to be considered accurate head movements of the subject must be at an absolute minimum in order to avoid distortions. His resolution to this problem of head movements was the introduction of a bite bar [25]. A bite bar significantly reduces the head movements of a subject in order to increase the spatial resolution of eye movement recordings [26]. He added arms projecting outward from the bite bar to enable the starting eye position to be measured with greater accuracy by realigning the double image of each arm seen when focusing on a grid or wall with a

predetermined horizontal line on the wall [26], a device still often used today when precise measurements are required [27]. By introducing these controls, the accuracy and reliability of eye-movement recordings were increased, as this provided a standardised method of determining the true starting position of the eye rather than using more generic method such as using the assumed natural position of the eye, or the centre of the visual field.

Javal tried to observe eye movements during reading using afterimages, however, he found that this method was not best suited to this and found it difficult to apply accurately. Instead, he devised a method of attaching a device or physical object directly to the eye itself and recording the movements on a smoked drum. Another ingenious method devised by Javal was to measure the deflections of light from a mirror attached to his eye which removed the problem of a cumbersome device attached to the eye that could interfere with the ability to record quick eye movements [28]. Each time the bulge of the moving cornea bumped the microphone, a saccade could be counted [29]. An approximate measure of the location of these fixations could be obtained by inducing an afterimage in the subject's eye with a bright light and then asking them to report the location of the afterimage as they read [30].

The progression provided by Javal was a turning point for eye movement research as this is the first attempt at directly and objectively measuring eye movements [24]. All previous methods relied upon self-observation or observing another person or more indirect measures such as the use of afterimages. A more sophisticated method of measuring saccades was attempted by Huey (1898) who recorded "jerks" or saccades by direct observation when reading. However, he could not keep up when a person read at their normal speed [31]. He, as did Javal, identified a need for an accurate recording of eye movements, but this seemed impossible to him without having to directly attach something to the eye. He attempted to overcome this by capping the cornea with a cup and recording the movements on a smoked drum. He also used a second drum to record time – an electric time marker wired to a clock marking quarter seconds (250ms). However, he soon realised that the temporal resolution of this method was poor as 250ms is not precise enough to measure eye movements, especially from one fixation to the other [32]. These observational methods generally were limited by the accuracy and memory of the observer [33].

Towards the end of the century, a more objective method to record eye-movements was required. Delabarre (1863-1945), proposed that the solution to many of the problems faced by psychologists of the time would be to devise an accurate method for measuring eye movements. He did manage to successfully reproduce a set of eye movement recordings and shared his crude method with the scientific community and welcomed suggestions for improvement. The proposed method was to attach a plaster of Paris cast over the cornea, and movements were recorded on a smoked drum. The eye was anaesthetised with cocaine and so did not cause pain to the participant (interestingly, Delabarre was often the subject of his own experiments!) [31]. This method lent itself to recording slow eye-movements with great accuracy however in a similar fashion to the system proposed by Huey, it was unable to record more natural movements with the same degree of accuracy. Both Huey and Delabarre were able to gain valuable first insights into the mechanisms and characteristics of eye movements. However, their devices of measurements were criticised for impeding motion and straining the eye. Dodge (1899) took a different approach to the measurement of eye movements and incorporated the use of reaction time

chronometry or reaction-times (reaction-times are also often termed latencies in eye-movement research). He believed that the reaction time of the eye had a unique significance to psychology and physiology. To measure the reaction time of the eye, in other words, or latency to initiate a movement, Dodge presented a stimulus to the blind spot of the eye whilst the eye was at rest (fixating on something in the visual environment). Provided that the duration that the stimulus is presented for is sufficient in length, the natural movements of the eyes caused by peripheral stimulation will bring the stimulus into view. The duration of the stimulus that is required is equal to the reaction time of the eye [34]. This methodology is still widely used today to show differences in the eye-movement latencies of gamers [35], deaf individuals [36] and athletes [37].

20th Century and Beyond

The 20th century saw the focus of eye movement research shift towards the reliability and validity of methods. Scientists wanted more objective, accurate recordings of eye movements and so there was a drive towards making more accurate measurements. Subsequently, and thankfully, the use of direct attachments to the eye fell out of favour and were replaced by less invasive photographic methods, which caused no pain or discomfort whilst remaining simple and accurate.

Dodge continued his research into eye-movements into the 20th century. At this point, he discovered what is now referred to as saccadic masking [30], where the eye is effectively blinded as it travels one from the fixation point to the other. Although this was predominantly based on self-observation of his own vision and also reports from a subject who stated that they could not perceive text as they moved their gaze around. However, self-observation was not accurate enough to unpack the mechanisms of what was going on sufficiently, so another method would need to be developed to investigate this further [38].

Photographic methods were the next evolution in eye-movement research and gradually began to replace the self-observation methods. Dodge and Cline (1901) developed a photographic apparatus to record eye movements in which the surface of the cornea was used as a reflector. The reflection from the cornea was measured rather than directly photographing the eye. The bright lines of light produced gave a clear record of eye movement. This improved clarity over photographing the eye directly allowed the images obtained to be magnified considerably while still maintaining the accuracy of the measurement [39]. This method was used by Dodge and Diefendorf (1908) to compare the eye movements of controls and the “insane” (researchers were much less politically correct in those days) [40]. They looked at the eye-movement traces of healthy controls versus those with either dementia, manic-depression or epilepsy and found that the latency of pursuit-related eye movements was greater than that of simple ocular reaction for all groups except for the manic-depressive group. The difference between latencies for each group however was variable.

Judd (1905) was another early adopter of using photographic methods to record eye-movements. To overcome the problems of photographing the eye with sufficient clarity, he developed a kinetoscopic eye tracker. Here, a small particle, placed on the cornea, which moved with the eye made eye-movements easier to measure. It was also capable of taking binocular recordings and could be used to measure eye movements between fixations. It worked by taking multiple photographs in rapid succession [41]. The photographic method was utilised by various researchers of the time, many of whom applied this

to the study of reading and studying itself, investigating concepts such as pause duration and reading time [42], reading Latin [43], and how people view pictures [44].

Photographic methods were also used to investigate certain pathologies or medical conditions, providing comparisons of eye movements in healthy subjects and a range of different patient populations. Jasper and Murray (1932) for example, looked at the differences in eye movements between stutterers and normal speakers during oral reading, observing that stutterers tend to fixate more than a normal speaker and show greater differences between oral reading and silent reading than normal speakers do, suggesting a disequilibrium of the nervous system in those who stutter [45].

Despite many advances in the field, however, there were still problems faced by researchers when it came to designing a suitable method of measuring eye movement. These issues included obtaining the necessary level of accuracy, removing or reducing movements of the head and eliminating the effects of the heartbeat [27]. Hartridge and Thompson devised their own photographic methods which consisted of a low powered microscope and both reference and corneal light sources attached to a frame, as well as a mouth plate that fits in the subject's mouth. It enables eye movements to be measured independently of head movements while removing the need to constrain head movements [27]. They refer to another method devised by Lord and Wright (1948) which consisted of two photoelectric cells onto which a beam of ultra-violet radiation is focused, after passing through the eye and reflecting off the retina. The output of each photocell is then amplified and fed into an oscillograph and give vertical traces only. The traces are photographed simultaneously, and eye movements can be deduced from the photographed traces [46].

Methods of eye-tracking measuring the muscular activity rather than the movement of the eye itself were also developed around the mid-20th century. White, Eason and Bartlett (1962) used electrooculography to measure the reaction times of the eye when asked to fixate as quickly as possible on light stimuli at different points across the horizontal plane.

Electrooculography (EOG) is an electrical method of recording eye movements that measure the corneo-retinal standing potential that exists between the front and back of the eye. It works on the principle of the eye as a dipole. Electrodes are placed either at the top and bottom or to the left and right of the eye. As the eye moves the positive or negative side of the retina is detected by one of the electrodes (depending on the direction the eye moves). The resting potential is constant, and so any potential detected gives a measure of the eye's position [47].

Further development and refinement of these techniques led to methods resembling the techniques for recording eye-movements which we are familiar with today. One early iteration of this was the portable eye marker system developed by Rockwell, Overby and Maurant (1968) which was used to investigate the eye movements of drivers [48]. Using this system, they were able to map the eye movement patterns of drivers to a visual scene [49]. Additionally, Loftus et al (1975) described an online eye movement recording system capable of overcoming the two major disadvantages associated with previous recording methods: the tedious and time-consuming analysis process, and the limited uses of such recording methods. The system consisted of a display, a device to measure eye position and record this as electrical signals, an analogue to digital converter and a computer [50].

As stated at the start of this chapter, the visual system receives highly detailed information from the small part of the visual field that the eye is fixating at that moment in time. However, the target for each detailed fixation is planned using information gathered from low-resolution peripheral vision. The relationship between peripheral information and eye movements has intrigued researchers. This relationship could only be investigated, however, if subjects were instructed to hold their eyes still, or if stimuli were presented tachistoscopically prior to an eye movement occurring. These limitations were able to be overcome in the 1970s by coupling the system that was measuring eye movements with the system that was presenting stimuli to the subjects [51][52][53]. During the 30-50 milliseconds in which the eye is in flight to saccade to a new location, the visual system's sensitivity is greatly reduced. To trigger a change in the visual stimulus during that brief period, the saccade must be detected within a few milliseconds of onset, the appropriate stimulus change calculated by the computer, and the screen display refreshed. Using a limbus reflection system that sampled eye position every millisecond, researchers were able to produce 'saccade-contingent display control' [51][54]. In such experiments, the characters of a line of text could be changed while a subject was reading, and hence the amount of information that a subject detected peripherally could be assessed. The development of gaze-contingent paradigms is considered to be a highly significant advance in eye movement research, with far-reaching practical applications. Such paradigms provide a method to explore not only eye movement behaviour but also for eye movement behaviour to manipulate a device.

As the tools to measure eye-movements became more sophisticated, so did the understanding of the range of different range eye-movements and other metrics. Often these were employed to learn more about psychiatric conditions. Paradigms such as smooth pursuit where an observer is required to track a moving target [55] were used to investigate eye movements in a range of populations and disorders [56], such as Alzheimer's [57], schizophrenia [58] and autism [59]. An anti-saccade, a term first coined by Hallet (1978), is a saccade away from a stimulus [60]. Anti-saccade paradigms are now often used to investigate deficits of inhibition and more specifically to estimate injury to the frontal lobe [61]. This is done by assessing the brain's ability to inhibit a reflexive saccade by asking the individual to make a saccade in the direction away from the stimulus [60]. Guitton, Butchell and Douglas (1985) found that patients who have lesions in their frontal lobe lacked the ability to suppress saccades in the direction of the stimulus and thus performed worse on anti-saccade tasks than healthy participants, however patient performance on the pro-saccade task, looking towards a target rather than away from it, matched that of the healthy participants [62]. As eye-tracking techniques became more precise, more also became known about the intricacies of certain metrics. For example, the near-linear relationship between the amplitude/peak velocity and duration of a saccade – termed the saccadic main sequence and first identified by Bahill - is implicated in a host of different neurological and psychiatric disorders [63][64]. Whilst pupil dilation was identified as a marker of cognitive effort [65]. The 1990s saw the emergence of eye-tracking technology that could be used alongside fMRI. This technology was used to classify the generators responsible for saccades and pursuit eye movements. This setup consisted of infrared light generated outside of the scanner by LEDs, guided into the head coil via optic fibres and onto the participant's eyes. Light reflected from the iris was detected by two additional optic fibre cables [66]. This allowed spatially and temporally accurate measurements of eye movements and brain activity to be taken simultaneously. Another advancement of the 1990s was the control of

computer functions via eye movements. These utilised electrical potentials recorded via EOG which were transformed into a cursor on a computer display [67].

Conclusions

Today, eye movements are a common metric among scientific investigations by a range of specialisms including psychology, biology, pharmacology, biomedicine and rehabilitation. The tracking of eye movements has been used to successfully investigate function in humans, non-human primates, canines, rodents and fish. Eye movements are easy to measure, quantify and analyse and can be manipulated in sophisticated behavioural paradigms. In current society, eye-tracking is a popular and versatile technology found in a multitude of domains. From traditional academic research to learn more about oculomotor processes [68] to user-design to enhance pilot-cockpit interaction ([69], to market research to ensure optimal product placement or packaging design [70], to providing sports competitors with the edge in high stakes competitions [71]. Recently, there has even been a push to use eye-movements for diagnostic purposes in medicine [72][73] [74] Additionally, eye-tracking no longer requires expensive items, with inexpensive consumer-grade equipment available to enthusiasts such as the Tobii 4C Eye Tracker (Tobii Tech, Sweden). The ubiquitous presence of webcams on laptops may also open the use of eye-tracking in remote areas and internet research, given some of the advances in developing algorithms to turn laptop grade webcams into eye-trackers able to provide data on par with eye-trackers costing many times more [75][76]. This chapter has summarised the long rich history and evolution of eye-tracking, from utilising rudimentary techniques such as mere observation, or plaster-casts of the eye, to the intricate eye trackers we use today, permitting a greater understanding of the function, mechanism and application of eye movement research. Eye-tracking has a wealth of applications [77] and will continue to be pivotal to many domains of research.

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