Peeking into the Mind's Eye: Electrooculography in Text Comprehension Research

By Reg Hackshaw, EdD

It's not about what technology can do, it's about what you can do with it.

– Common[1]

Abstract. Where individuals position their visual attention, the speed at which such positioning occurs and how long they pause or fixate on parts of a sentence provide indirect glimpses into the internal mental events associated with the understanding of written language. Text comprehension – defined as cognitive processes involved in extracting meaning through silent and attentive visual inspections of textual material – ultimately determines whether a reader graduates from one state of knowledge to another.[2] Text comprehension is fundamental to the experiences of reading and learning. Findings from text comprehension research are important considerations in the design of effective instructional systems that encourage content area mastery in students.

Because the mind follows as well as commands where the eyes look, this article surveys the history of recording bioelectric signals associated with a reader's eye movements using analog and later digital electrooculography. Several examples of the technology illustrate this method of data collection in empirical studies of text comprehension. The article concludes with a discussion of how academic programs in polysomnography (PSG) can provide the technical skills for students interested in this field.

A Century of Research

For over 100 years, investigators have documented the binocular eye movements (EMs) known as saccades that reposition a reader's fixation field to successive words or phrases in a sentence.[3-5] The visual perception of text is limited to the fixation time between EMs. Nineteenth century experimenters reported the sequence of stops and starts during reading tasks by direct observation with handheld mirrors. Decades later, custom-built mechanical devices attached to the eyeballs became the preferred data collection method to record the roving eyes of readers. One experimenter even resorted to dosing his subjects with cocaine to reduce the discomfort of such invasive procedures.[3] The first non-invasive EM recorder was devised in 1901 and relied on a light beam reflected from the reader's cornea to project images on a moving photographic plate.[6]

Vacuum tube technology, which facilitated the detection of enemy submarines during World War I, led to instruments with sufficient signal amplification to detect bioelectric activity.[7, 8] Studies comparing EOG to the more established photographic methods of data collection demonstrated the utility of this new technology.[9] Biomedical recorders configured with amplifiers for monitoring brain wave activity (EEG), cardiac rhythms (ECG), muscle activity (EMG) as well as ocular dynamics (EOG) evolved into the polygraphs used by sleep technologists and research-driven educators.[10-11] These analog workhorses could generate ink-on-paper tracings to produce interpretable graphic records when properly calibrated and maintained (see Fig 1).

Incidentally, biomedical recorders built to assess an individual's credibility by the detection of deception predated the use of clinical and research polygraphs. Generally, these "lie detectors" were limited to recordings of cardiovascular activity, respiration and sweating as measured by electrodermal activity.[12] Another interesting fact in polygraph history concerns the first continuous, electrographic recording of nocturnal REM sleep. The study was conducted at the University of Chicago on a polygraph that used vacuum tube EOG/EEG amplifiers.[43]

The computerization of EOG in addition to other physiologic measures emerged in the 1960s from research in motion sickness related to air and space travel.[14, 15] Digitized systems helped relieve human scoring technicians from the time consuming chore of manually reducing big data sets with minimal scoring bias. Examples of vintage mechanical calculating aides used by EOG scorers appear elsewhere in the historical literature.[16]

Signal Source and Processing

The cornea and retina of the eye resemble the oppositely charged terminals of a battery. Electrodes placed near the left and right temples monitor horizontal rotations of this electrical dipole as a subject performs left to right scans

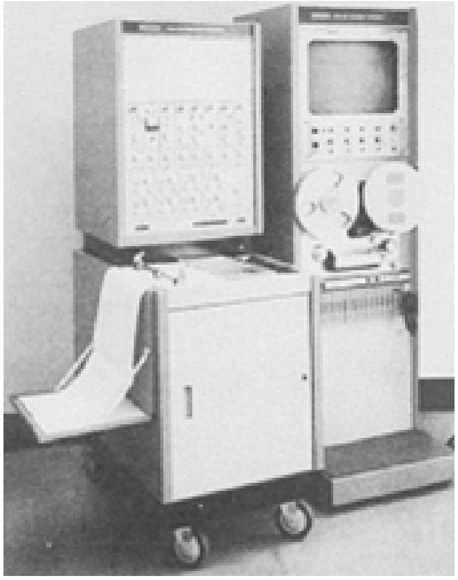

Fig 1. A paper recording, monitoring and storage system for biomedical data consisting of an ink-writing polygraph (left), monochrome monitor (top right) with a multitrack, magnetic tape recorder bottom right; adapted from the Beckman Historical Collection.[13]

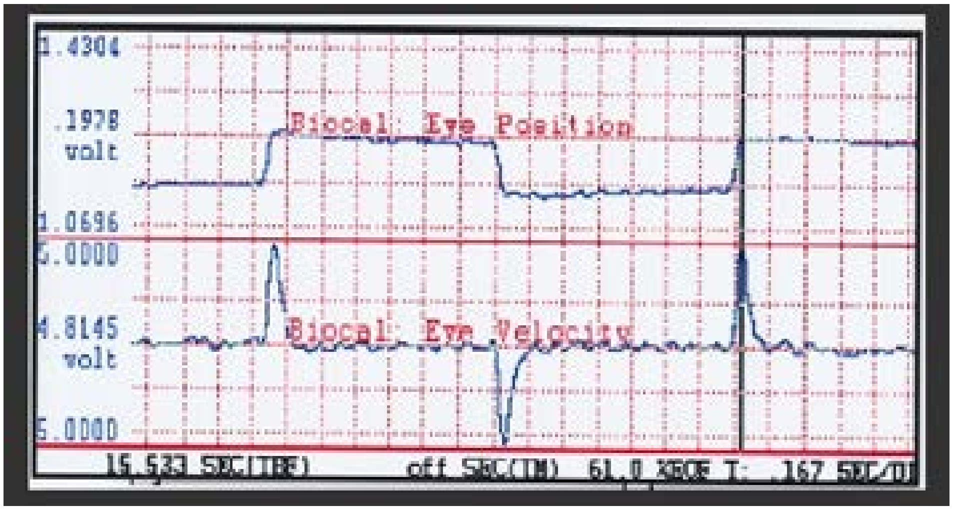

Fig 2. Signal voltages over time (in sec) for eye position using DC amplifier and saccadic velocity using AC amplifier; subject fixated on two letters in succession appearing at left and right margins of text screen. Fixation time is the inter-saccadic interval on velocity channel. Data set is from a Beckman recorder with signals ported to a Dataq digitizer with Windaq viewer.[17]

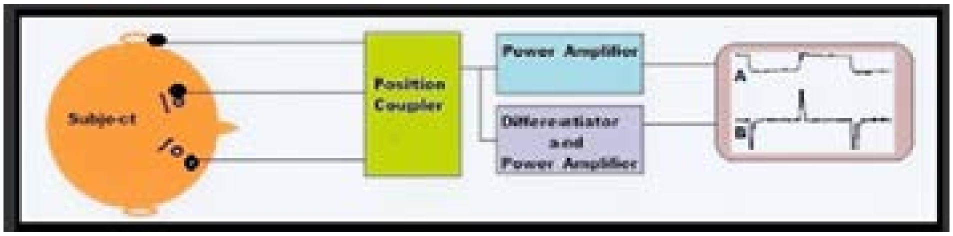

Fig 3. Schematic diagram of biocal signals from electrode placements, to position coupler, to amplifiers, and finally to a dual-channel, monitor, which displays eye position (A) and saccadic velocity (B).[20]

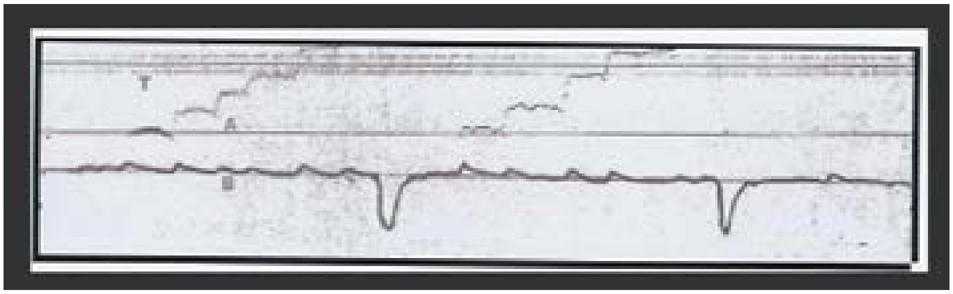

Fig 4. Signal amplitudes shown over time for a subject reading two lines of text. Eye position (A) shows upward, stair-step signature as eyes move from word to word; downward return-sweeps move eyes to next text line. Polarity of differentiated position signal (B) was reversed in keeping with actual direction of EMs. Timing signal (T) marks one-second intervals.[19]

during reading behavior. A third electrode, placed on an electrically neutral site such as behind the subject's ear, serves as a reference point. An electrically shielded cable routes infinitesimally small voltages to a polygraph for filtering, which sifts desired signals from competing signals.

The following differentiating stage increases the filtered voltage difference between the two electrode placements while rejecting electrical noise common to both placements relative to the neutral site. Without this essential feature, background noise would obscure the desired signal.

In addition to *differential* amplifiers, some equipment manufacturers introduced an analog signal processor known as a *differentiating* amplifier. Processor output was proportional to the rate of change in the signal associated with eye rotations. The differentiation of eye position provided velocity data.[18] This quantity, defined as the distance covered by an eye rotation over time, approximates reading speed measured in either letters per second or words per minute. Differentiating amplifiers encouraged electrographic investigations of reading speed in text comprehension research. Velocity is a practical measurement for detecting fixations because the eyes remain relatively still between EMs. Signals exceeding an empirically determined minimal velocity are defined as EMs (see Fig 2). The term I-VT refers to the identification of EMs and fixations by velocity thresholds. A television monitor and an ink-writing unit convert the signals into visible patterns for either immediate viewing or post-acquisition analysis. One of the first reports of this instrument configuration surfaced in 1950.[19] The basic configuration remained unchanged until the introduction of digital data acquisition (see Fig 3).

Meaningful data collection using antique polygraphs required recording technicians with a practical knowledge of medical instrumentation and biomedical electronics. A hands-on ability to troubleshoot faulty recording sessions "on-the-fly" with minimal downtime was essential. One technician described this technology as WYSIWYG or "what you see is what you get."[10] Post-acquisition editing to remove ECG, muscle activity or intrusive artifacts from a broken lead serving as an antenna for radio frequency interference was not an option with analog technology. (When the author temped as an electro-diagnostic technician at an uptown New York City hospital, an improperly attached patient lead would pick up pirate radio broadcasts from an adjacent apartment complex and transmit the signals to a recording polygraph's EMG channel!)

267	283	200	350	283	283	733	266	183
The Egyptian engineer of 5,000 years ago may have used a simple wooden								
	467	200	1201	333	367	583	568	
device called a weightarm for handling the 2.5 to 7 ton pyramid blocks.								

Table 1. Fixation Durations Measured During Reading. Mapping fixation times (in msec) onto words gives information about lexical access times. Values indicate total time subject spent fixating on each word or phrase.[23]

Fig 5. A sub-notebook PC from Acer (left); Dataq's dual-channel, data-logger (center); Heathkit's dual-channel, EOG unit (right) withelectrode patches and cables (foreground) comprise a compact, student-friendly, system for empirical studies of reading behavior.[35]

Understanding Comprehension

I do believe something very magical can happen when you read a good book.

– *JK Rowling*[21]

According to Monika Pluzyczka from the University of Warsaw, the cognitive movement in psychology from the 1970s promoted the use of EM recordings in text processing research.[3] In contrast to behavioral psychologists, who considered unobservable mental states as topics ill-suited for scientific inquiries, cognitive psychologists advocated hypothesized relationships between perception and mental events. Thought provoking articles such as: *The Theory of Reading from Eye Fixations to Comprehension,* and *What Your Eyes Do While Your Mind is Reading* published in 1980 and 1983 respectively, intrigued researchers.[22, 23] Some individuals even suggested fixation signatures could reveal hidden processes involved with rendering images in the mind's eye. However, a more cautious position warned against "fanciful flights" and supported "the solid ground of sound experimentation and rigorous inference."[24]

Jin Ong was a professor at the Southern College of Optometry in Tennessee.[25] Previously, he was a graduate assistant to the experimentalist and EOG historian, Elwin Marg.[8, 26] Although a strip chart recording from nearly 70 years ago displays velocity signals from a case study involving a brief reading task (see Fig 4), Ong described the first known use of I-VT in a controlled, study of reading behavior.[27] His subsequent work with a Beckman polygraph (see Fig 1) analyzed reading efficiency under different experimental conditions as well as the precision and reliability of EM measures.[28, 29]

The expanding presence of mini-computers in EM laboratories required software applications to expedite data analysis.[30, 31] An avalanche of studies documenting digital methods for quantifying basic EOG parameters (namely: eye position, saccadic velocity and fixation time) included some notable duplication of efforts.[32] Applications typically used I-VT algorithms because of the marginal computational demands placed on the hardware available at that time.[30-33]

Eye tracking refers to mapping individual fixation times onto specific words through computer-assisted biocalibrations. This capability provides moment-to-moment insights regarding mental processing that accompanies reading behavior.[30] For example, the data set in Table 1 indicates the term weightarm requires more fixation time to process, which suggests the term's meaning as a mechanical device was not available for immediate access from the reader's vocabulary or lexicon. Furthermore, longer fixation times recorded at the end of the sentence suggest the reader needed additional time to integrate words viewed between EMs into a meaningful sentence. The findings are consistent with the Eye-Mind Connection that hypothesizes a minimal time lag between text perception and cognitive processing.[22, 23]

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An accelerated reduction in the physical footprint of data acquisition systems began in the 1990s.[3] The miniaturization of biomedical instruments, the availability of signal digitizers and the personal computing revolution, paved the way for desktop EOG. A generation of hybrid systems emerged consisting of analog recorders coupled with data loggers operating on PC platforms (see Fig 5). By the beginning of this century, all-digital systems had emerged as the gold standard for collecting physiologic data.[10] Within the past decade, the Phywe company based in Gottingen, Germany began marketing an all-digital EOG/ECG/EMG unit recommended for high school instruction.[34] The pocket-sized unit offers

Wi-Fi data streaming to an Android or Ipad tablet along with suggested teaching points including EMs, measuring fixation intervals and speed reading techniques.

When Comprehension Fails

…with weightless hands night is lulling the furious tide,and one by one images recede, one by one words cover their faces.

– *Octavio Paz*[45]

Pluzyczka has documented the explosive growth in eye recording and tracking articles submitted to academic journals during the years leading up to 2014.[3] In her *Review of Electroocculography*, principle author Uzma Singh writes

Eye movements also reveal information on cognitive processes of visual perception, such as visual memory, learning, or attention. If it is possible to infer these processes from eye movements, this may lead to…aware systems that are able to sense and adapt to a person's cognitive state.[36]

The identification of an EM signature associated with the brain in autopilot mode while reading would benefit both students and teachers. An intelligent device interacting with the user could infer whether an EM pattern indicates waning attentional involvement with the reading material.

Metacognition is a state of *mindful* or attentive focus during mental or physical activities. This learned skill encourages individuals to reflect on whether they are actively processing information acquired through reading behavior. However, during episodes of *mindless* text inspection, the "eyes might arrive at the bottom of the first page successfully enough… but there will be no understanding of the sentences…[37] Mindless text inspection, where visually fixated words are unattended is not consistent with the definition of reading as a behavior that advances students to higher states of knowledge.[2] "Don't teach til you see the direction of their eye movements" was one special educator's pointed response to managing the vacant stares of students.[46]

A lack of interest in the subject matter, distracting background noises or a sleep deficit can precipitate comprehension failure. For example, the Epworth Scale – a standard diagnostic inventory for evaluating excessive daytime somnolence (EDS) – includes the likelihood of falling asleep while reading as a presentation of EDS.[44] Despite the prevalence of mindless reading, investigators rarely expressed much interest in this phenomenon.[38] However, pioneering efforts by Francoise Vitu are a noteworthy exception. Her post-

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doctoral research, which relied on corneal reflection method for eye tracking rather than EOG tracking, was published in 1995. Vitu compared EM signatures of readers who received meaningful text samples to samples devoid of linguistic content.[39] Although more recent studies delved into the mindless reading experience, Reading Hall of Fame inductee, Karen Wixson voiced concerns that EM research in this area is still experimental.[40]

A go-to place for further information is the Eye Tracking Research and Applications (ETRA) website.[41] ETRA's list of corporate underwriters for their yearly conferences is worth reviewing as part of any targeted job search. A recent literature review focusing on cutting-edge applications of EOG technology in human-computer interactions is another valuable information source.[42]

Technical Training

"An understanding of the inner mechanism of any tool used by the researcher should be part of [their] intellectual repertoire."

– *Nathaniel Kleitman*[43]

The technical skills necessary to use EOG and ETRA in text comprehension research (and in the wider field of human cognition) are multi-disciplinary. A survey course on the physical and natural world can provide a context for subsequent courses in medical instrumentation theory, medical terminology and physiologic event scoring. An introduction to electricity is a good foundation course. Appropriate courses in the life sciences include: anatomy, physiology, as well as an elective in physiological or cognitive psychology. Quantitative literacy, in addition to written and oral communication courses, are essential practical skills. Many junior colleges offer these courses through their accredited PSG and biomedical electronics degree programs.

Summary and Conclusions

Although more accurate methods for recording EMs are available, EOG technology is still one of the most cost-cutting ways to collect data about cognitive processes underlying reading and learning from textual materials. Empirical findings can assist in the design of effective instructional aides that contribute to expert performance. EOG technology coupled with artificial intelligence has the potential to improve human-computer interfaces by inferring the cognitive states of users with an acceptable level of accuracy. These developments highlight directions in the field through the combined efforts of electro-diagnostic techs and engineers as well as neuro and cognitive psychologists.

Registered sleep technologists with structured training combined with clinical experience in physiologic recordings and signal recognition (selecting appropriate filter settings to discern the slow EMs of drowsiness from the rapid EMs of dream sleep, for instance); possess a marketable skill set. This skill set can transfer to employment positions using EOG and ETRA. In addition, a practical understanding of such concepts as sampling theory, signal analysis, networking and data file management gained from conducting PSGs on digital acquisition systems are assets to include in a job-seeker's professional portfolio.

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