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Potential Eye Tracking Metrics and Indicators to Measure Cognitive Load in Human-Computer Interaction Research

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Abstract: **Eye tracking has a deep-rooted history in the field of medical and psychological research study as a method for investigating human visual behavior. It is a reliable and non-intrusive technology which opened up innovative approaches of solving problems or getting insightful data, but also emerging as a new filed of research. Due to recent technological advances, eye tracking technology has revolutionized human technology interaction. Even though, many practical issues exist concerning the use of eye tracking as an input device in human-computer interaction (HCI), this method is progressively used in user research, usability evaluation, user interface design, user experience design and in many other everyday applications and products. The objective of this research paper is to present potential indicators and their significance to measure cognitive load within the frame of human-computer interaction. We discussedvarious eye movement metrics and indicators which can be employed to measure cognitive load in the context of HCI research.**

Index Terms: **eye tracking, eye movement, blink, pupil size, saccades, fixations, gaze, user research, cognitive load, visual attention, eye tracking metrics, eye tracking indicators**

I. Introduction

People constantly explore their natural world by moving their eyes. They look around rapidly with less conscious effort but with regard to the highly structured task, the research study has provedthat individuals look at what they are working on. The eyes do not wander randomly. Eye contact and gaze direction are essential indicators in human communication, for example, in regulating interaction and turn taking, establishing socio-emotional connection, or indicating the target of our visual interest (Kleinke, 1986). The eye is the main gateway to the brain (Brigham et al. 2001; Ellis et al., 1998). Gaze activities reveals cognitive process and provides insights about thought process and intentions(Land &Furneaux, 1997).

Eye tracking method is useful in manydomain, from psychological study and medical diagnostic to usability studies and interactive, gaze-controlled applications. The focus is to provide a meaningful starting point for researchers, designers of interactive technology and assistive technology professionals wishing to gain deeper insight into eye tracking metrics and their significance.

Primarily, eye activities were primarily studied by physiological evaluation and observation. Basic eye movements were classified and duration estimated for precise measurement of eye movements. The first generation of eye tracking devices was uncomfortable. The revolution and advancement of the eye tracking technology paved way for thedevelopment of the first ‘‘non-invasive’’ eye tracking device in the early 1900s (Wade &Tatler 2005) that was established on the principle of photography and light reflected from the cornea. It can be considered as the first ancestor of the current widely used video-based, corneal reflection eye tracking systems. The innovation of discreet camera based methods (Morimoto & Mimica 2005) and explosion of computing ability enriched eye tracking information, allowing the gaze as a main control mechanism for disabled people (Ten Kate et al., 1979). This has become a motivational factor to extend eye tracking techniques over a large area, which are discussed later.

Tracking people’s eye movements can benefit HCI researchers understand the factors that increase the cognitive load at a given point of time. Eye movements can also be recorded and used as control signals to empower users to interact with computer interfaces directly without using mouse or keyboard input or touch. In the coming chapters we given an overview of eye tracking technology, eye tracking in HCI research, cognitive load, potential eye tracking indicators to measure cognitive load and methodologies used to implement gaze interaction.

II. History of Eye Tracking in Human-Computer Interaction

Research study shows that various methods have been commonly used to track eye movements 100 years ago (Javal, 1878/1879). The early non-invasive eye tracking method, using light reflected from the cornea was established by Dodge and Cline (1991). It recorded only horizontal eye position on a photographic plate when the participant's head is motionless. Later in 1905 Judd, McAllister and Steel used motion picture photography to capture the eye movements in two dimensions. In the first half of the twentieth century, researchers made progressive advances in recording eye movements by linking the corneal reflection and motion picture techniques (Mackworth&Mackworth, 1958). In 1930, Miles Tinker and his team started to apply photographic method to study the eye movements in reading (Tinker, 1963) and studied the reading pattern and eye movement speed.. In 1947 motion picture cameras were used to investigate the movements of pilots' eyesin the cockpit controls with regard to landing airplane (Fitts, Jones & Milton, 1950). This study represents earliest research study of usability engineering to study the users interacting with products and improve the product design.

The first head-mounted eye tracker was discovered by Hartridge and Thompson in 1948. Though it was a crude product in its form, it served to free the participants from tight constrains on head movements. Further it was developed by Shackel (1960) and Mackworth and Thomas (1962) and made it less obtrusive. In 1958, Mackworth and Mackworth developed a system to capture eye movements on the changing visual seen viewed by the participant and this led to the relevance of eye tracking to Human-computer interaction. Further the eye tracking technology advanced in 1970s and this paved the way for psychological theory to link eye tracking data to cognitiveprocess period (Monty & Senders, 1976; Senders, Fisher & Monty, 1978; Fisher, Monty & Senders, 1981).

In 1970s, significant efforts were made to technical enhancements to bring more accuracy and precision. The arrival of minicomputer provided necessary base for high-speed data processing and this led to the use of eye tracking data in real-time as a means of Human-computer interaction (Anliker, 1976). In 1970 psychologists who researched eye movements and fixations tried to evade cognitive issues such as learning, memory, workload and attention (Kowler, 1990). This scenario slowly changed when engineers developed better eye tracking system, psychologists started to investigate the relationshipbetween fixations and cognitive activity (Just & Carpenter, 1976a, 1976b).

Each decade, eye tracking has solved consistently new problems (Senders, 2000). As the personal computers were proliferated, the eye tracking technology pioneered its study to address the issues in the domain of human-computer interaction and began to examine how users navigate (Card, 1984; Hendrickson, 1989; Altonen, Hyrskykari and Raiha, 1998; Byrne *et al.*, 1999).During the 1980s user-computer communication was also emerged with the combination of eye tracking data (Bolt, 1981, 1982; Levine, 1984; Glenn *et al*., 1986; Ware andMikaelian, 1987).

Invasive methods were used initially, involving direct mechanical contact with the eye to detect the eye movements. An another technique also used, like bigger contact lenses to cover the cornea and sclera with a metal coil implanted on the edge for measuring the variations in an electromagnetic field while moving the metal coil along with eyes (Duchowski, 2003). Most modern eye tracking in human-computer interaction has shown a significant growth in exploring the usability of computer user interfaces. As the technology and technology enabled services were advancing and proliferating, eye tracking became a viable means to study the factors affecting human interaction and measure the cognitive load while performing tasks.

III. Eye Tracking Technology

Eye tracking technology comes with an eye tracker to measure the eye activity. It tracks our eye movement and help the researcher to understand the attention area of the visual field. The idea is simple but the method and analysis can be quite complex. In general, eye tracking information is gathered by means of either screen based or wearable eye tracker connected to a computer. Many of the eye tracking systems available today have two common elements: a light source and a camera.The infrared, light source is targeted toward the eye. Reflection of the light source together with noticeable ocular features for instance the pupil are tracked by the eye tracking camera. Most of the eye trackers existing today measure point-of-regard by the "corneal-reflection/pupil-center" method (Goldberg &Wichansky, 2003). The eye tracking information is used to analyzethe movement of the eye and finally the direction of the gaze. Information such as blink frequency, changes in the pupil diameter and other information related to the eye movements are also identified by the eye tracker.

Screen based eye trackers is a device which captures gaze data for research into behavior and eye movements, from fixation-based studies into micro-saccades as shown in Fig. 1. Wearable eye tracker is a device which captures natural viewing behavior in any real-world environment as shown in Fig. 2. This helps to understand how a person is looking at in real time as they move freely in any real-world setting and how people interact with the environment. Wearable eye tracking system opens up a wide range of opportunities in studying user behaviors.

Each eye data is interpreted into pixel coordinates position.

This kind of analysis will determine which feature is seen or what captures the attention, how eye moves and what content is overlooked. Graphs such as heat map and gaze plots are often produced to visualize the findings. Other than the visual attention, the eye data can be used to measure cognitive workload of a participant. The most commonly used metrics is Index of Cognitive Activity (ICA). Today with the advancement of eye tracking technology, anything with a visual element can be eye tracked and today it has become significantly important in research and design. The fields such as advertising, entertainment, packaging and interface design are widely benefitted from eye tracking from studying the user behavior. Modern day eye trackers provide possibilities to integrate additional biometric devices such as EEG, GSR or EKG to make the conclusion more concrete. The usage of eye tracking technology has extended to the sectors, like automotive, medical and defense to make the user safer. The growing newer areas like, advertising, entertainment, packaging and web design have

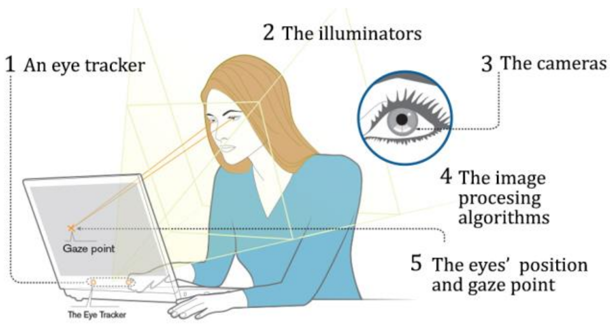

Fig. 1.Screen based eye tracking components of Tobii eye tracking

Image Source: https://www.tobiipro.com/learn-and-support/learn/eye-tracking-essentials/how-do-tobii-eye-trackers-work/

gained substantial insights from examining the visual behaviour

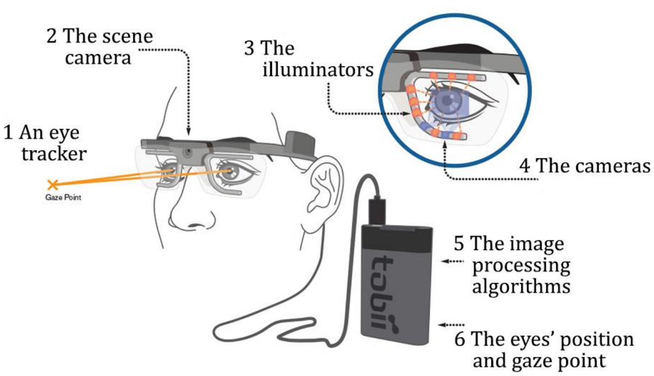

Fig. 2.Time versus location (communication fault)

Image Source: https://www.tobiipro.com/learn-and-support/learn/eye-tracking-essentials/how-do-tobii-eye-trackers-work/

of the end user.

IV. Eye Tracking in Human-Computer Interaction

Eye tracking is a method of tracking eye movementsdenoting to the point of user's visual gaze focused on the scene. Eye tracking concept has a long history even before computer interfaces (Fitts, Jones & Milton, 1950) and their findings are still useful today. As the technology advanced to the new highest of user interface and user experience, human-computer interaction is gaining more importance each day. Proliferation of computing devices such as smartphones, tablets and laptops with internet of things (IoT) justifies the need for better user experiences. Eye tracking can assist significantly in the evaluation of usability aspect of a product, app, website, or any interface in general. Eye tracking techniques gives invaluable data to understand the users mental model and the problems users face while doing a task.

Persons eye gaze is presumed to indicate the thought in relation to cognitive process (Just and Carpenter, 1976). This means that the eye movement can give dynamic evidence to person's attention in relation to a visual display.Calculating other features of eye movements like fixations can also uncover the amount of processing being applied to objects at the point-of-regard. HCI researcher defines the area of interest over some parts of display to infer useful information from the eye movement. This will enable the researcher can objectively evaluate the interface with eye tracking metrics and improve the human interaction (Goldberg &Kotval, 1999).

Eye movements provide many aspects of human cognition and this has become the scientific research tool in HCI and related disciplines like human factors and cognitive ergonomics. HCI and usability research studies have significantly researched the nature and effectiveness of information search methods on menu based user interfaces (Altonen, Hyrskykari, &Räihä, 1998; Byrne, Anderson, Douglas, &Matessa, 1999; Hendrickson, 1989) and also studied the characteristics that are associated with effective usability (Cowen, Ball, &Delin, 2002; Goldberg, Stimson, Lewenstein, Scott, &Wichansky, 2002; Poole, Ball, & Philips, 2004). Additionally, eye tracking technologies were broadly used in applied human factors research in air-traffic-control training (Hauland, 2003) to design user-friendly cockpit controls to reduce the error and in medical procedures to improve doctor's performance (Law, Atkins, Kirkpatrick, & Lomax, 2004; Mello-Thoms, Nodine, &Kundel, 2002). Eye tracking technology is also used in the areas of market research and advertisements to attract greatest attention (Lohse, 1997).

V. Potential Eye Tracking Metrics and Indicators to Measure Cognitive Load

This chapter summarizes the common eye tracking indicators to measure cognitive load in the HCI research. We discuss eye tracking metrics in order to investigate users' cognitive process and cognitive load. Eye tracking measures like task performance, visualization, blink, pupil dilation, saccade, fixation and scan path are discussed with other variables and their indicators. This can help many HCI researchers who use eye trackers to measure cognitive load. Each of the metrics can apply various measuring algorithms depending on the nature and context of the research.

A. Cognitive Task Analysis Metrics and Indicators

Cognitive task analysis (CTA) performed to measure the expected performance standard on a goal oriented task and the aim is to record the cognitive knowledge used by them (Clark & Estes, 1999). It helps the researcher to capture accurate and complete description of cognitive processes and decisions. There are many number of CTA methods currently in use due to the diverse path that the development of CTA has taken but one can choose any method fitting into the context. One can design simple to complex tasks or only complex tasks or only simple tasks to measure the cognitive load of a novice to expert users. The time taken to complete the task and number of steps taken to complete the task will indicate the cognitive load. Table 1 gives details of cognitive task analysis metrics.

Table I. Cognitive task analysis metrics and indicators

Metrics	Indicators
Time on a task (simple to complex)	Time taken to complete the task indicates more cognitive load.
Steps to complete the task	Number of steps taken to complete the task indicates more cognitive load.

B. Eye Tracking Visualization Metrics and Indicators

In commercial eye tracking systems, there are two kinds of visualization that is heat map and gaze plot. The heat map is graphical representation of data clustered data and their values represented in colour. Heat map is calculated by number of fixations and duration of fixation. A gaze plot is a map which shows movement sequence of fixations on a visual display in the order they occur. It is simply the user's eye path represented by circles as fixations and circle areas are proportional to fixation length. These two metrics can help the researcher to understand how user's mind works while performing a task. Table II gives details of cognitive task analysis metrics.

Table II. Visualization Metrics and Indicators

Metrics	Indicators
Heat map	It shows the number of times attention to a particular part of display.
Gaze plot	More steps to perform a task indicates more cognitive load.

C. Fixation Metrics and Indicators

Fixations are the most important element that eye tracking researchers analyze to make inferences about cognitive process. It is the stage where eye essentially stops scanning the scene and sticks to the central foveal vision in place so that the visual system can focus about what is being looked at. Gaze pints are the direct spatial spots of visual axis falling on the stimulus. They have (x,y) coordinate relating to its measurement. This is an output generated by the eye tracking hardware. If theeye tracking device is operating at 60 Hz, a gaze point will be generated typically every 16.7 milliseconds. Similarly, at 300 Hz, gaze points are spaced a mere 3 milliseconds apart. The number fixation indicates number of times the user looked at a specific area. Game points indicate what the eyes are looking at. Gaze points per second are collected based on the sampling rate of the eye tracker. If gaze points are very close in time or space, it denotes that where the eyes are locked and it is an excellent measure for visual attention. Gaze direction is the indication for the interface element for the currently cognitive activity (Darrell S. Rudmann, George W. McConkie, &Xianjun Sam Zheng, 2003).

Table III. Fixation metrics and indicators

Metrics	Indicators
Duration of fixation	A longer fixation duration describes issues related to extracting information, or it indicates that the object is more appealing (Just & Carpenter, 1976).
Fixation Count	The number of fixations on media indicates efficiency in information search.
Total number of fixation	Total number of fixations on media indicates efficiency in information search
Fixation spatial density	Fixations concentrated in a small area indicate focused and efficient searching (Cowen et al., 2002).
Fixations per area of interest	More fixations on a specified area signify that it is more perceptible, or more significant to the viewer than other areas (Poole et al., 2004).
On-target Fixation	Fixations on-target divided by total number of fixations. A lower ratio indicates lower search efficiency.
Time to first fixation on-target	The time-to-first fixation for each area of interest on all Media and indicates that an object or area has a better attention-getting properties (Byrne et al., 1999).
Average fixation count/duration	The average duration of the fixations within each area of interest on all Media. It shows how long the average fixation lasted for .
Fixation density	It is the number of gaze points inside a fixation event divided by the smallest area to record all gaze events (Brookings, J. B., Wilson, G. F., & Swain, C. R., 1996).
Fixation rate	The frequency of looking at some point per second. It represent attention.
Dwell time	Time spent in the same position and area. It indicates measuring the time the user remains at a search result after a click.
Gaze	Sum of all fixation durations within a specified area. It is best utilized to evaluate attention distributed among targets (Mello-Thoms et al., 2004; Hauland, 2003).
Gaze samples	A series of close gaze points or gaze cluster in space and time indicates a period where the eyes are locked towards an object.
Attention Switching Frequency	Measures the dynamics of visual attention using the total number of shifts between a set of area of interest per minute.

Fixations have two features from gaze points. The first feature is that fixations have duration besides a spatial (x, y) location and start and end timestamps. The second is fixations are directly measurable using gaze point-to-fixation conversion algorithm or fixation filter. It can be explained easily depending on the context. In a web page task, higher fixation on a particular area can indicate more interest in the target or the target may be complex (Jacob &Karn, 2003; Just & Carpenter, 1976). But in the case of search task, higher number of single fixations indicate greater uncertainty (Jacob &Karn, 2003). Similarly, the fixation duration is linked to theprocessing time related to the target being fixed (Just & Carpenter, 1976). It is an effort made to restructure these significant eye movements as meaningful as possible in terms of attention, visibility, mental processing and understanding.Areas of interest (AOIs) is very important aspect of stimulus. This is more contextual and can be defined either before the experiment or after the experiment. The metrics applied to AOIs are related to transition that is number of transitions between two AOIs. The transition can be looked into in terms of dwell time and fixations within AOIs. Metrics closely related to fixations are listed with their indicators in the Table III.

D. Saccade Metrics and Indicators

Saccade is another eye tracking measure used to move the fovea quickly from one to another point of interest. This indicates to a shift between two fixations. Saccade can be triggered voluntarily or involuntarily.The length of a saccade and its amplitude are sequentially associated. When the eye voluntarily moves from one fixation to another and takes 30-80 milliseconds to complete. One can measure the velocity and length of saccades to investigate the cognitive load. The higher the load, the longer the saccades (Victor Manuel, Victor M. García-Barrios, Christian Gütl, Alexandra Preis, Keith Andrews, Maja Pivec, Felix Mödritscher& Christian Trummer, 2004). During saccades, no encoding happens and so cannot reveal the complexity of an interface. But, regressive saccades can provide clue for measuring processing difficulty (Rayner &Pollatsek, 1989). Table IV shows, metrics of saccade and their indicators in detail.

Table IV. Saccade metrics and indicators

Metrics	Indicators
Length of saccade	Duration of changing the point of fixation and this indicates visual attention and cognitive relevance.
Number of saccades	Number of involuntary, abrupt, rapid, small movements of both eyes simultaneously in changing the point of fixation. (Goldberg &Kotval, (1999).
Saccadic amplitude	It is the distance travelled by a saccade from onset to offset. Larger saccades indicate more meaningful cues (Goldberg et al., 2002).
Saccadic regression	Events that move in the opposite direction to the text. Regressions indicate the presence of less meaningful cues. (Sibert et al., 2000).
Saccade duration	The time duration of a rapid movement of the eye between two fixation points. More saccades

E. Scanpath Metrics and Indicators

Scanpath is another indicator which embodies the spatial structure of eye movements performed by a participant during task. It unfolds visual attention indicating visual context attended. There is no clear method to average the scanpath but the difficulty of averaging the scanpath is due to spatial and temporal causes. The gaze plot that represents saccades and fixations with straight lines and circles respectively is used as a common method for scanpath visualization. Though there are many algorithms to discover relationship in different scanpaths, Scan path Trend Analysis (STA) uncovers the most appropriate path of multiple users on visual screen. Table V shows, metrics and indicators of scanpath to measure the cognitive load in eye tracking study.

F. Pupil Dilation Metrics and Indicators

Pupil dilation is a significant indicator of cognitive load in eye tracking research study. It is an involuntary reflex and the pupil can vary in diameter from 1/16 inch to more than 1/3 inch. Psychologists have acknowledged that changes in pupil dilation indicates effortful cognitive processing. Past research also confirms that the pupils dilate when the difficulty of the task and their cognitive effort to solve it increases. Video cameras and infrared illuminators are used in the eye tracking technology to record the eye position, cornea reflections and the pupil dilation. Using eye tracker, the researcher can examine the response of pupil dilation in relation to the information on the screen and the behavioral choices during the experiment.

Table V. Scanpath metrics and indicators

Metrics	Indicators
Scan path duration	Duration of a complete sequence of fixations and interconnecting saccades. A long lasting scan path signifies lesser effectiveness (Goldberg &Kotval, 1999).
Scan path Length	A lengthier scanpath denotes less efficient Searching (Goldberg et al., 2002).
Spatial Density	Lesser spatial density signifies more direct Search (Goldberg &Kotval, 1999).
Scanpath Direction	The path in which a whole order of fixations and interlinked saccades occur. This can indicate participant's search strategy (Altonen et al., 1998).
Scanpath Regularity	Deviance from a normal scanpath denote search issues related to interface (Goldberg &Kotval, 1999).
Saccade/Fixation Ratio	This is a comparison between time spent on searching (saccade) and time spent on processing (fixations). Here, higher ratio implies more processing or less

Human pupils dilate for numerous reasons, including memory, cognitive struggle, excitement, pain and so on (Beatty, 1982). When a user performs cognitively demanding tasks, pupils dilate 1-2 seconds in response to mental workload of the task (Beatty, 1982) and constrict gradually after the task is finished (Kahneman& Beatty, 1966; Hess, 1972). To measure changes in cognitive load under a range of tasks, the average percentage change in pupil size can be analyzed. One has to be very careful to distinguish the exact cause that activated the pupillary response because there are various causes which can triggers pupillary response, like light reflex, changes in illuminous and error due to gaze angles. Table VI shows metrics and indicators related topupil dilation.

Table VI. Pupil dilation metrics and indicators

Metrics	Indicators
Pupil size	The size of the pupil in response to the media. Pupil size could be used as a manifestation of cognitive workload (Marshall, 2000; Pomplun&Sunkara, 2003). It is an involuntary reflex and the pupil can range in diameter from 1/16 inch (1.5mm) to 1/3 (8mm). Changes in pupil dilation accompany effortful cognitive process.

G. *Blinking Metrics and Indicators*

Blinking activity is another metric to another layer of information for measuring cognitive load. Blinking is mostly an involuntary act during which the eyelid covers the pupil and cornea from the light reflect resulting in raw data points missing the x, y coordinates information. For analysis, fixation filter can be used to remove the missing points and infer the information correctly into fixations.

The blink rate and latency will provide information for deeper understanding about the state of the attention of the participant.

Table VII. Blinking metrics and indicators

Metrics	Indicators
Blink rate	The blink frequency per minute. The blink rate and pupil size could be considered as a manifestation of cognitive workload (Bruneau, Sasse, & McCarthy, 2002; Brookings; Wilson, & Swain, 1996; Marshall, 2000; Pomplun&Sunkara, 2003).
Blink duration	Closure time duration of a blink in ms. Provides information about cognitive load and attention.
Velocity of blinking	Velocity attained while eye lid closing and opening. Gives information about cognitive load and attention.
Blink latency	Latency in the saccadic system is around 200 ms, and corresponds to the time from the onset of the stimulus to the initiation of the eye movement. Provides information about cognitive load and attention.

High blink rate and low blink rate has been found to indicate high mental effort (Siyuan Chen, Julien Epps, Natalie Ruiz & Fang Chen, 2011). Similarly, research shows that increase and decrease in the blinking velocity and a decreasing degree of the eyelids' openness are sings of increasing tiredness.

To detect eye blink, the researcher needs to look at the center point of the pupil. When the eye is open, there will be white pixels on the image which will help to calculate easily the center point of the pupil. If eye is closed, there will not white pixels of pupil on the image. A count variable is created to calculate the center point. The variable is taken as '1' when the eye is open and the variable is taken as '0' when the eye is closed. These variables will help to detect the eye blink metrics and their indicators as given in the Table VII.

CONCLUSION

Eye tracking technology is an important device to measure and analyses cognitive load in the context of HCI and visual computing. It appears as a new and promising area of work. We reviewed the usage of eye tracking system in HCI research and discussed the relevance of eye tracking metrics and indicators for measuring cognitive load. Our approach was to look at all possible eye tracking metrics and indicators holistically so that they can be possibly used in any type of HCI research in terms of measuring cognitive load. The focus is to provide a meaningful reference for HCI researchers so that they can identify metrics and make their own recipe for the study of attentional, cognitive states or process.As the eye tracking technology becomes increasingly more intelligent, less invasive and easier to use, the use of eye movement tracking technique going to increase manifold.

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