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Eye Movement Profile: Quantification of Cognitive Workload

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Abstract

Cognition itself is a qualitative variable but can be quantified in terms of different directly or indirectly associated factors. The eye movement profile is one of them that has been reported since the nineteenth century. Many researchers have considered eye movement as a window to access cognitive abilities in different areas if everyday activities. Moreover, a significant amount of original research and review articles have tried to establish various models to interpret work demand in terms of cognitive workload. However, those past articles are limited to very specific aspects of eye movement profile and with respect to specific tasks. The objective of the current review article was to formulate a model covering every possible aspect of eye movement research concerning human cognition specified with frequently considered eye movement events/profiles. The observation of the current review supports the past research that eye movement is strongly associated with cognition and eye movement profiles could be considered as potential markers for future cognitive psychology research. Significant evidence has been found for Pupilometry, Blink Profile, and Saccade Profile to prepare a model that can interpret cognitive workload. However, the lack of evidence was observed against the Fixation Profile strongly connected with cognition, which might be a relevant future scope in eye movement research. This review article singly would be helpful in the future to interpret cognitive workload through eye movement research across a diverse group of everyday activities.

Keywords: Eye Movement; Cognitive Workload; Pupil Diameter; Blink; Fixation; Saccad

Introduction

Cognition is a qualitative measure of the mental process could be quantified in terms of various determinants, which have a direct or indirect effect on cognition including quantitative and qualitative measures. To name a few, The Montreal Cognitive Assessment (MoCA) [1], Mini-Mental State Examination (MMSE) [2], standardized Mini-Mental State Examination (SMMSE) [3], Electroencephalogram (EEG) [4,5], neuropsychological vertigo inventory (NVI) [6] and vastly using Eye Movement Recording (EMR) since decades [7,8] are globally considered as a method to quantify cognitive workload. The Eye Movement Recording is the interest of the current review article to discuss how different eye movement profile could be considered to quantify cognitive workload during performing different activities.

Eye Movement and Types

Eye movement is the orbital change in the position of the eye leading to change in the visual field to acquire visual signals. The eye can move voluntarily (to achieve a goal) or involuntarily (to response stimuli). Saccades, smooth pursuit, emergence, and vestibulo-ocular movements are the four basic types of eye movements [9,10]. In saccadic eye movements, the eye moves ballistically changing the point of fixation, which includes smaller movements during reading to larger movements during watching around a room [9,11]. Smooth pursuit eye movements correspond to the slow and voluntary movement of the eye to track the moving objects to keep on the fovea [9]. These two types of eye movement are conjugate eye movement that means both the eyes move in the same direction but in Vergence, eye movement is either convergence (near objects) or divergence (far objects) type when each of the eyes targeted the objects of different distances from the viewer [9,12]. Vestibulo-ocular eye movement is a compensatory eye movement that stabilizes the image on the fovea during head movement or locomotion. During head movement, vestibule-ocular eye movement occurs for the same distance but in the opposite direction of the head movement to make the focused objects stable in the fovea [9,10].

Eye Tracking

Eye movements have significant qualitative and quantitative importance to predict human behavior and perception. Since the late 19th century, scientists considered different techniques to measure eye movements, generally known as Eye Tracking. Visual observation techniques through mirror [13], required magnification lenses for larger eye movements [14] and microscope for small eye movements [15]. Later eye tracker adopted needed to be attached with the eye as a contact lens with a lever to record the movement of the eye on the recorder [16,17]. Lord and Wright adopted a photoelectric method to record eye movement based on the recording of corneal reflex [18]. Besides the photoelectric method, Yarbus considered another method used a mirror attached in a small rubber suction cup that was based on the recording of the reflected beam of light [19,20]. Another most popular method concerning the measurement of corneo-retinal potential difference through electrooculography (EOG) to measure eye movement was first considered by Schott, Meyers, and Jacobson [21-24]. With the advancement of optical engineering, eye tracking has now become easy in terms of usability [25-28]. Significant amounts of researches have addressed the relation of eye movements and respective neuronal mechanisms [29-32].

Eye Movement and Cognition

Eye movements expedite a proficient sampling of visual information of interest. Sometimes, eye movement sampling was used to predict social behavior and emotions of a human being [33]. Many scientists have discussed that precise controlling mechanism of eye movements are the intensive future research scopes [34-37]. However, many researchers have considered eye movement as a potential tool to understand the different aspects of human behavior in the field of medical science, psychology, social sciences, human-computer interaction and computer science to name a few [38-46].

After the invention of the relationship between eye movements and speech perception/memory/language processing [47], many researcher have considered eye movement to investigate cognition and perceptual processing that has been discussed in the review of Huettig, et al. [48]. Rayner discussed that eye movement profile (fixation durations) was found to be influenced by cognitive processes [7,49]. Rayner also commented that the eye movement profile could able to provide significant information about human information processing [7,49].

Underlying different cognitive processes, another review article claimed that eye movements reveal a significant amount of psychological progressions [50]. Their thought primarily based on two significantly explored eye movement research domains, visual search, and reading, to understand the mechanisms of key aspects of controlling eye movement. To understand the mechanism of eye movement control, the controlling mechanism and relationship between where and when to move the point of eye fixation are necessary to recognize the cognitive process replicated through eye movements. Further, the researcher concluded that where' and 'when' model of eye movement control are psychologically and physiologically separable [51,52]. Considering the above phenomenon, Simon and John concluded with a hope that future eye-movement research would reveal more cognitive controlling processes behind eye-movement patterns [50].

Henderson and his co-researcher recorded eye movements of twelve participants while performing four tasks: reading, pseudo-reading, scene search, and scene memorization to investigate whether the performed task could be accurately classified through the eye movements [39]. For that, they used multivariate pattern classification [53,54] to train and tested on eye-movement measures to conclude that if it is possible to identify the tasks that participants engaged in their eye-movement pattern. The results suggested that eye movement provide significant information to classify engaged tasks further claiming that movements could be used to understand a person's cognitive state [39] corroborating with the top-down eye movement control theories for complex tasks [55-58]. Moreover, they have commented that besides the cognitive state, eye movements are also systematically influenced by the performed task [39]. Therefore, before designing a future study to understand human cognitive behavior one should precisely consider the tasks to be performed. However, a significant amount of study has considered evaluating human behaviors in everyday tasks like reading [39], visual searching [59], tea making [60], sandwich making [61], tapping a sequence of targets on a table [62], driving [63], table tennis [64], and cricket [65].

A recent study has considered eye movement recording along with several neuropsychological scores from ninety participants from three age groups (younger adults, older adults under 65 years and over 65 years of age) to understand the effect of age-related cognition on saccadic eye movements (SEMs). They have observed that SEMs are associated with and could be able to highlight the age-related decline of processing speed and attention in prosaccade and antisaccade tasks. They have also discussed that decrease in latency is related to processing speed decline and modification of executive attention plays a vital role in control and correct saccades, therefore, defining specific cognitive functions [66]. Another recent review article discussed that research of attention and eye movements are significantly explored [67-69] and pointed out that specific regions of the oculomotor system forms a spare network within the brain further expecting to process the information by many regions integrated with cortical connections and cooperating with the cognitive process [8]. In recent years, Konig, et al. commented that eye movement researches have reached a significant stage that could be integrated with other research methodologies to investigate the brain and mind [8]. Indeed, eye movement is significantly associated with cognitive loads and eye movement research is useful and could be considered as a measure to assess cognitive workload for single as well as combination of tasks [70,71].

Eye Movement Profile and Cognition

Eye movement profiles represent every segment or events of eye movement which is broadly classified into four i.e., pupil diameter, blink, fixation, or visual intake and saccade. These are significantly considered and globally accepted measures in eye movement research. The following sections are highlighted with the purpose to discuss the different eye movement profiles and how they can be connected with the cognitive workload.

Pupil Diameter / Pupilometry

A significant amount of the theoretical accounts reveal that observed changes in pupil diameter are influenced by required cognitive effort [72] and pupil diameter plays a crucial role in analysing memory tasks [73]. Further, it is evident that the cognitive process demands a mental effort of attention and memory [74-77]. Progressive increasing task demands proportional increased mental effort further reflecting in changing pupil diameter. Indeed, the pupilometric profile is important to quantify the cognitive workload of a certain task. More specifically, pupil diameter has been found to be dilated as an influential effect of mental workload and vice versa [78-81]. However, ambient illumination has an influence on pupil diameter [82]. Therefore, before commencing pupil diameter as a potential marker for any future scientific research exposed to ambient illumination should critically considered.

Blink Profile

Researcher in the mid-20th century established that eye movement profile of blink rate could be a potential marker of attention to defining cognitive tasks [83,84]. A significant volume of evident reflected that decreased blink rate is associated with suppressed visual information [85], vocal difficulties to produce long sentences during a conversation [Cummins, 2011], more attention encountered tasks [83,84] and visually demanding tasks to minimize the chance of escaping insightful information [83,86-88]. Therefore, higher cognitive work demand manipulated with decreased blink rate [89,90]. In line with the findings of a decrease of blink duration as a function of increased workload [91-93], most recent research of the current century observed that blink duration was found to decline as a function of increasing cognitive workload (Table 1) [78]. In case of more visual information to process central systems of the observer control to blink less [85]. Moreover, Meyer and Meyer, et al. addressed that the efferent nervous system controlling brain mechanisms is responsible for the muscular controlling of eyelids [94,95]. However, it is evident to produce a significantly higher frequency of blink for older children and adults than younger children [96,97]. John discussed that rate of blinking was found to increase as a function of time on the task [98]. Factors like eye injury, medication, and disease also have an influence on eye blink [99].

Fixation Profile

Three main overlapping or parallel events of Encoding of visual inputs, sampling of peripheral field and planning for next saccade takes place within a minimum fixation duration of 100 to 150 ms or within a typical fixation of 250 to 300 ms [100]. In modern techniques, instead of traditional detection of two separate fixations for even a single gaze, one larger and longer visual intake event has detected [101]. It is evident that fixations are strongly associated with the time to the evaluation of the task [60,61]. A limited number of fixations focused on irrelevant objects for a particular task, for example, fixation moves from the grasping and moving items to the next item to be moved [60,61]. Since the last century, the research focussing on the eye pauses (fixation) and the fundamental relationship with the cognitive process was the topmost priority [102,103]. Just and Carpenter proved that in sentence processing tasks, eye fixation and mental operations are systematically correlated, further establishing the proportional relationship between duration of gaze and duration of said tasks [104]. Moreover, a recent article discussed different aspects of fixations as a window to the cognitive process [8]. In this line, Barreas conclude that a higher cognitive workload can be associated with a significant increment of fixations count per second (Table 1) [70]. However, in spite of highlighted researches on the role of eye fixation study in cognitive psychology; there is a lack of significant evidence to identify a potential fixation model that could interpret cognitive work demand, being a specified scope of future research. Rather, eye fixation could be a potential marker to deliberate efficiency in reading, problem solving and information processing tasks (Table 1) [105]. Moreover, Loftus observed that fixation count could be the potential predictor of recognition memory for learning tasks [106]. Another group of researcher reported that the variation on fixations have a link with attention levels and working memory [107,108]. In particular, they claim that fixation duration enhances when an increment on the working memory. Interestingly, fewer fixations per word and more fixations per line were associated with the densely grouped, single-spaced document during performing reading tasks [109]. In line with similar observations towards difficult tasks, during artwork viewing, difficult processing was found to be associated with longer fixation duration (Table 1) [17]. On the other hand, longer fixations have produced for smaller and densely presented texts [109] and in the learning phase, later memory was appeared to be positively correlated with fixation duration [110]. Moreover, a wide range of fixation duration is responsible for the amount of information acquire with respect to different fixations [61]. Similarly, longer fixation duration was observed during observing face image then the natural scene which may be due to the critical analysis of the facial features (an individual's gender, age and familiarity, and their expressions) further revealing that different pattern of visuomotor activity is generated by face and natural scene [111]. Therefore, it is unclear whether fixation duration is directly associated with cognition and might be an important future research scope in the area of eye movement research.

Saccade Profile

A saccade is the ballistic movement of the eye corresponds to the amount of visual search on a scene. Generally, for understanding saccade is the distance between two fixations and the saccade count be quantity of fixation minus one. The close relation between attention and saccade is an established phenomenon [112-114]. Hoffman and Subramaniam and Shepherd, et al. (1986) claimed that before the occurrence of a saccadic movement participant first attend to that location [114,115]. Supporting the observations of Kowler [112], Hoffman and Subramaniam reported that to some extend oculomotor control of eye movement depend on attention [114].

Some studies from the current century suggested that there is a direct relationship between saccade count and cognitive workload. More specifically, the higher cognitive workload is associated with more number of saccades (Table 1) [70,107,108,116]. Therefore, the saccade profile not only could be a valid marker to measure cognitive workload but can also detect cognition in earlier states than eye fixations [70]. Average saccade velocities were also found to be enhanced with the enhancement of cognitive workload (Table 1) and reported to predict driver's perception of developing road accidents (Table 1) [71]. Smit and Gibergen suggested that at the early stage of saccades visual stimulus could speed up than initiate and guide the saccade. They also discussed that very short period of saccade latencies are probably due to the combination of sensory and motor time delay, not the time required for the computation of saccade properties [117]. However, the intrinsic value of visual information found to have a lesser but significant influence on the motor controls of saccades would keep in mind during designing of future research considering the saccade profile [118].

Parameters	Interpretation in terms of cognitive work load/ Performance		Influential Factors	References
	Increase in quantitative value of the profile	Decrease in quantitative value of the profile		
Pupil Diameter	Increase in pupil diameter is associated with higher cognitive effort	Decrease in pupil diameter is associated with lower cognitive effort	Environmental Illumination, Chronologic Age	Cabestrero, et al. [80]; Bruno, et al. [81]; Barry, et al. [82]; Ulf and Ferne [78]; Batmaz and Ozturk [79]
Blink Count/ Frequency	Lesser cognitive load leads to increased blink count/ frequency	Increases cognitive loads to lesser blink count/ frequency	Age, Task Duration, Eye Injury, Medication and Disease	Volkmann, et al. [85]; Fukuda, et al. [89]; Hayley [90]; Van; Orden, et al. [91]; Veltman and Gaillard [92]; Zeghal, et al. [93]; Ulf and Ferne [78]; Conrad [96]; Lohr [97]; John [98]; Desai [99]
Average Blink Duration	Less cognitive workload produce increased average blink duration	Higher cognitive workload produce shorter average blink duration		

Fixation/ Visual Intake Count / Frequency	Increased fixation count/ frequency is associated with lesser searching efficiency and higher cognitive workload	Decreased fixation count/ frequency is associated with higher searching efficiency and lesser cognitive workload		Buswell [17]; Tichomirov and Poznyanskaya, [102]; Winikoff, [103]; Konig, et al. [8]; Barreras [70]; Rudmann, et al. [107]; Chen, et al. [108]; Just and Carpenter [104,105]; Kolers, et al. [109]
Average Fixation/Visual Intake Duration	Increased average fixation duration reflects difficulty in extracting information/ more task difficulty	Shorter fixation duration reflects easy to extracting information/ less task difficulty		
Saccade Count/ Frequency	More difficulty towards the selection of a target/ higher cognitive workload leads to more number of saccade count/ frequency	Less difficulty towards the selection of a target/ less cognitive workload leads to less number of saccade count/ frequency	Intrinsic value of visual information	Barrios, et al. [116]; Chen, et al. [108]; Rudmann, et al. [107]; Barreras [70]; Biswas and Prabhakar [71]; Smit and Gisbergen [117]; Xu-Wilson, et al. [118]
Average Saccade Velocity	More task difficulty/ enhanced cognitive workload produce high average saccade velocity	Less task difficulty/ reduced cognitive workload produce less average saccade velocity		

Table 1: Eye movement profile as a function of cognitive workload/performance and others influential factors.

Conclusion

Observation of the current review article corroborates with the observation of Rayner [7,49], Simon and John [50], Huettig, et al. [48], Henderson, et al. [39], Konig, et al. [8], Barreras [70], and Biswas and Prabhakar [71] that the eye movement profiles have a significant correlation with the human cognition and the eye movement could be considered as a potential method to interpret the cognitive abilities of the participants engaged in the diverse group of daily activities. In particular, an eye movement model has been prepared (Table 1) on the basis of significantly proven eye movement profiles of Pupilometry, Blink, and Saccade which would be helpful in the future to interpret cognitive workload across a diverse group of everyday activities. However, future eye movement research scope could be effective on Fixation Profile finding the link with cognition has been inadequately reported.

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