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Visual Performance under Varying Illumination Conditions while using an Indigenously Developed Wrist Wearable Computer

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ABSTRACT

Ambient illumination conditions have significant impact on users' visual performance while carrying out onscreen reading tasks on visual display units, especially smaller screen sizes. Present study assessed the visual performance responses of different ambient illumination levels during onscreen reading on Wrist Wearable Computer (WWC) developed for the command-control-communication between the control room and the soldiers operating in remote locations. Ten (10) Indian Infantry soldiers performed two different types of loud reading tasks on the display of WWC under three different ambient illumination (mean ±SEM) conditions namely, Indoor controlled (450.00±10.00 lx), Outdoor daylight (11818.7±582.91 lx) and Indoor dark (0.12±0.03 lx) environments. While reading, participants wore an eye tracking glass which recorded the eye movement responses. Visualisation techniques were used to predict the association of illumination levelof surrounding with visual performance of the user. Subjective legibility rating was also applied to understand participants' preferences towards physical attributes of the onscreen information and illumination level. Results indicated that illumination had a significant effect on eye movement parameters like fixation frequency, fixation duration and scanpath length while completing the tasks. Overall, participants performed better under indoor controlled illumination conditions in terms of fixation profile and scanpath length, apart from improved subjective legibility ratings as compared to other two illumination conditions. Future research attempts need to be directed towards the optimum performance of the display across wide range of ambient illumination conditions and to establish how the display of indigenously developed wearable computer performs in comparison to other such displays available across the globe.

Keywords: Wrist wearable computer; Illumination; Eye movement; Visual performance

1. INTRODUCTION

Ambient illumination affects visual performance while carrying out onscreen tasks[1-5]. Defence personnel often conduct operations under challenging illumination conditions affecting their visual performance, influencing combat performance. Majority of the military operations are performed through Command-Control-Communication-Computer Intelligence Surveillance and Reconnaissance (C^4ISR) where a screen based task is quite frequent. Dismounted soldiers operate in remote locations, maintaining bidirectional information exchange between the field and Command Control Centre, using a communication device. A wrist wearable computer (WWC) with a small size display, ensuring maneuverability, is suitable for soldiers' operations. However, reading from small sized screen may render poor legibility under inadequate illumination condition and demand higher cognitive workload, causing accidents. Literature indicates important criterion considered for optimizing the design of WWC, e.g., system efficacy during outdoor activities under different weather conditions like rain and varying temperature[6-7]; musculoskeletal stress, mobility hindrances due to weight of WWC and it's impacts on users' center of mass[8] ; heat generated by WWC[9]. Ambient illumination affected cognitive responses including reading performance[10], visual performance[11] and visual workload[12] while using hand held display unit[11] and office computer[12]. Critical consideration of illumination demand of a specific task was important for optimizing that particular task[12]. Shieh and Lin (2000) measured visual performance under different ambient illuminations and observed better visual performance in 450 lx ambient illumination than 200 lx[1]. When character identification was performed under different indoor illumination conditions of white and yellow lights, 'white light and illumination level of 500 lx'was found to be best[5]. Jacobsen (1986) observed faster response time and lower error in colour discrimination while using Cathode Ray Tube display under darkness with intermediate raster luminance[13]. Image identification deteriorated from dark indoor ambient illumination to brighter outdoor environments due to high reflectivity of hand held displays[14].

Recently, a WWC has been developed by Defence R&D Organisation, M/o Defence, GOI for Indian soldiers for communication under diverse conditions of complete darkness to glaring sun light. Present study was aimed to understand the efficacy of this WWC in terms of visual performance under various illumination conditions while performing given

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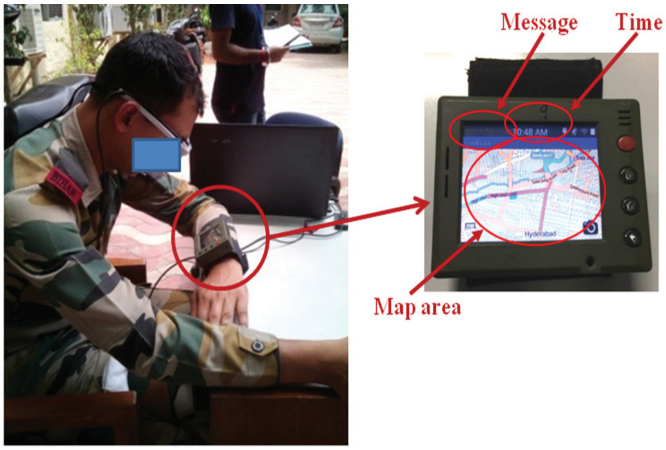


Figure 1. Different 'Areas of Interest' on Wrist Wearable Computer (WWC) Display for given reading tasks.

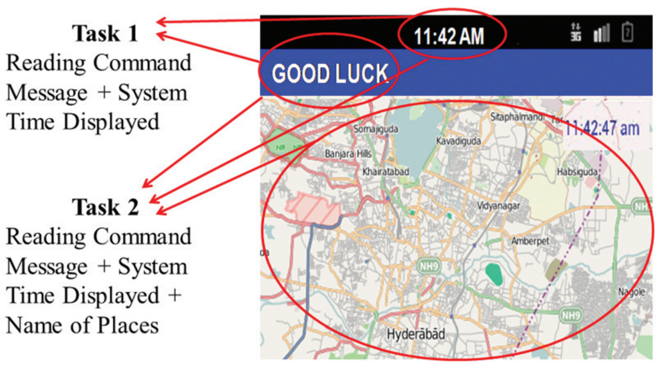


Figure 2. Screenshot of WWC display giving details of study design for task1 and task2.

Table 1. Ambient illumination, humidity and temperature (Mean±SEM) as observed while carrying out task1 and task2

Ambient	**Indoor Controlled (I)**	**Outdoor Daytime (O)**	**Indoor Dark (D)**
Illumination (Lx)	450.0±10.00	11818.7 ±582.91	0.12 ±0.03
Relative Humidity (%)	46.2 ±0.27	53.2 ±0.48	44.9±0.34
Temperature(°C)	26.7 ±0.22	31.7 ±0.31	26.1 ±0.23

Table 2. Combinations of font family-type-size for task 1 and task 2 carried out under different illumination levels

Font family (FF)	**Font size-type (FST)**	**Task (T)**	**Abbreviations**
Sans Serif (SS) (Arial)	Large-Bold (LB)	Task 1 (T1)	SSLBT1
		Task 2 (T2)	SSLBT2
	Huge-Normal (HN)	Task 1 (T1)	SSHNT1
		Task 2 (T2)	SSHNT2

Foot note:Task 1 (T1):Reading Command+Time; Task (T2): Reading Command+Time+Places in MAP area.

reading tasks. It was hypothesised that the WWC will perform best under comfortable condition of Indoor illumination.

2. METHODOLOGY

2.1 Participants

Ten (10) Indian Infantry Soldiers with Mean±SEM age of 33.6±2.21 years, volunteered for the study. Inclusion criteria was Shape I Infantry soldiers with 6/6 visual acuity without wearing any corrective lens. Exclusion criteria were recent eye infection, history of eye surgery,discomfort or pain in eyes while using digital display media.

2.2 Wrist Wearable Computer

A Wrist Wearable Computer (WWC), indigenously developed by Defence Research & Development Organisation, Ministry of Defence, Government of India, was used for the study (Fig. 1). Physical dimensions of WWC were: Length 10.5cm, Breadth 7.7 cm, Depth 2.5 cm, Weight 0.245 kg and the strap circumference 24.0 cm - 33.0 cm for wearing the device on user's wrist. The device operated in Android platform (v4.0x) with a dual-core cortex-A9 and 512 MB RAM. The display used for the experiment was resistive LCD with a 4 inch touch interface.

2.3 Study Protocol

The experimental protocol was first approved by institutional ethical committee (Ref no: IEC/DIPAS/D-1/2 dated 8 December 2015). Volunteers were explained the purpose of the study and they signed informed consent.

Participants performed two different reading tasks (Fig. 2) under three different illumination levels i.e., Indoor Controlled, Outdoor daytime and Indoor Dark. Lux meter (HTC, model no. LX-102A, India) was used to measure illumination levels and a portable weatherstation was used to note the ambient temperature and humidity at the beginning of each experiment. Values of ambient illumination levels, humidity and temperature are given in Table 1.

Study design for task 1 and task 2 are given in Fig. 2 and Table 2. Combinations of font family, type and size for the onscreen reading tasks were selected based on recommendations given under previous study conducted at the same laboratory with the same device[15]. Participants adjusted screen brightness level under each illumination condition as per their individual convenience and readability for optimum task performance.

The tasks involved loud reading (Fig. 2) by the participants, during which eye movement data were recorded. Participant wore WWC and placed his hand in a comfortable position for optimised viewing. The average distance between participants' eye and WWC display ranged between 45.6 cm - 57.4 cm. Participant was then fitted with Eye Tracking Glasses (ETG, M/s Sensomotoric Instruments (SMI), Germany) and calibration was performed by standard protocol given in the instrument manual. Eye movement parameters were recorded during each trial of 1 minute duration using 'iViewETG 2.7'software (M/s SMI, Germany) at a sampling rate of 120 Hz[16]. Each participant completed a total number of 12 trials 3(Illumination)×2(Font Type-Size)×2(Task)=12. Data for

Table 3. Levels of significance for different illumination, font family, size, type and task conditions while carrying out loud reading tasks with WWC.

Independent factors	Parameters	Levels of significance			Pair-wise comparison		
		F-value	Degrees of freedom	p-value	I vs. O	I vs. D	D vs. O
Illumination	FF	6.870	2,18	0.006*	0.02*	1.000^{NS}	0.02*
	AFD	0.667	2,18	0.525^{NS}	0.74^{NS}	1.000^{NS}	1.000^{NS}
	SpL	0.348	2,18	0.711^{NS}	1.000^{NS}	1.000^{NS}	1.000^{NS}
Font type-Size	FF	0.876	1,9	0.374^{NS}			
	AFD	0.910	1,9	0.365^{NS}			
	SpL	0.151	1,9	0.707^{NS}			
Task	FF	10.013	1,9	0.011*			
	AFD	0.501	1,9	0.497^{NS}			
	SpL	25.000	1,9	0.001*			

FF- Fixation Frequency, AFD- Average Fixation Duration, SpL- Scanpath Length, I-Indoor, O-Outdoor, D- Dark; * - Significant at p≤ 0.05, NS - Not Significant

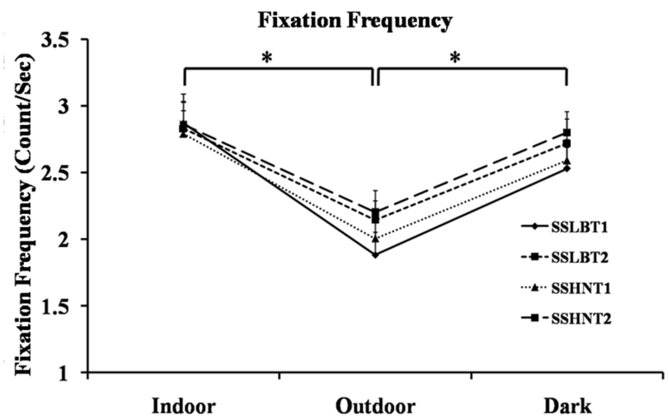


Figure 3. Fixation frequency changes during task 1 and 2 under different conditions of illuminations and font attributes while using WWC.

different illumination conditions were recorded on different days for each participant.

Eye movement data was analysed in 'BeGaze3.7' software (M/s SMI, Germany) and presented in two models i.e., average value of relevant parameters (Fixation Frequency,Fixation Duration and Scanpath Length) and visualisation techniques (Heat Map, Scanpath and Focus Map).

Legibility rating was obtained after finishing each tasks under various experimental conditions by applying a three point rating scale i.e., unsatisfactory, passable and excellent. The results were reported in terms of percentage of population choosing each component of the scale (Table 3)[17].

A three way repeated measure ANOVA was applied (Statistical Product and Service Solutions (SPSS), Version 20, M/s IBM, USA) to evaluate the responses of dependent variables under the combined effects of illumination, font type-size and tasks. Once an overall significance was obtained, Bonferroni post hoc test was conducted to identify significance level of individual pairs. A value of p≤0.05 was considered as statistically significant.

3. RESULTS

Eye movement and visualisation parameters were recorded while participants carried out reading tasks, while legibility ratings were collected after each task was finished. However, due to word limit constraints only a few important eye movement parameters have been reported in this paper.

3.1 Fixation Frequency (FF)[17, 23-24]

The results of repeated measure ANOVA revealed (Table3, Fig. 3) an overall significant effect of illumination conditions on Fixation Frequency (FF) $F_{(2,18)}=6.87, p<0.05$. Bonferroni post hoc test indicated significant changes when outdoor illumination condition was compared with indoor and dark illumination conditions, respectively, at $p<0.05$. Significant changes in FF at the level of $F_{(1,9)}=10, p<0.05$ were observed during performance of individual tasks. However, FF did not change significantly for font type-size combination at $F_{(1,9)}=0.876, p>0.05$.

3.2 Average Fixation Duration (AFD)[17,23-24]

Various illumination conditions $F_{(2,18)}=0.66, p>0.05$, font type-size combinations $F_{(1,9)}=0.91, p>0.05$ and both the tasks $F_{(1,9)}=0.50, p>0.05$ did not confer a significant effect on AFD (Table 3, Fig. 4).

3.3 Scanpath Length[25]

Scanpath Length (SpL) was significantly influenced by both tasks $F_{(1,9)}=25, p<0.05$. However, illumination $F_{(2,18)}=0.348, p>0.05$ and the font type-size combinations $F_{(1,9)}=0.151, p>0.05$ did not significantly affect the changes in SpL (Table 3, Fig. 5).

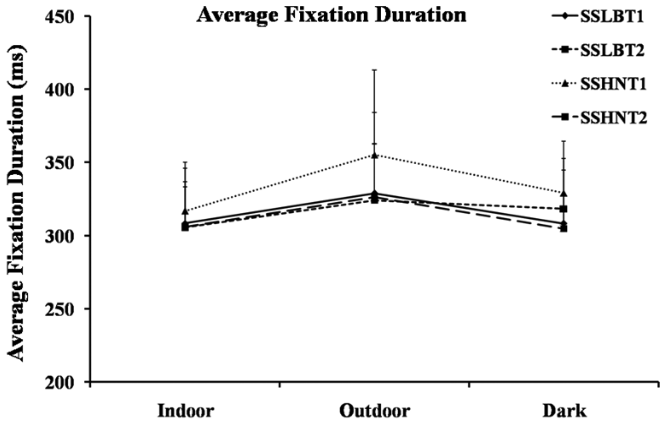


Figure 4. Average fixation duration changes during task 1 and 2 under different conditions of illuminations and font attributes while using WWC.

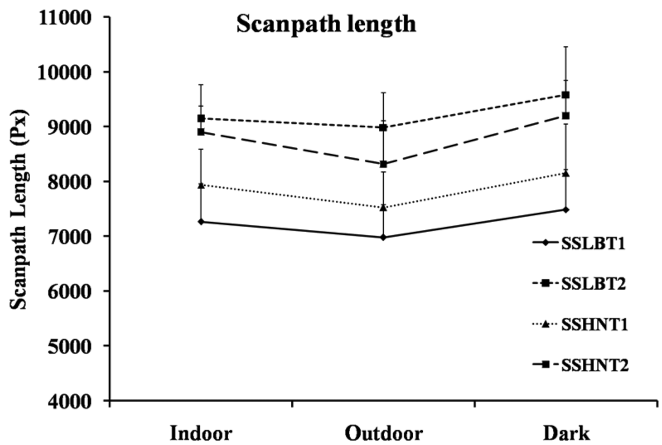


Figure 5. Scanpath length changes during task 1 and task 2 under different conditions of illuminations and font attributes while using WWC.

3.4 Heat Map[26]

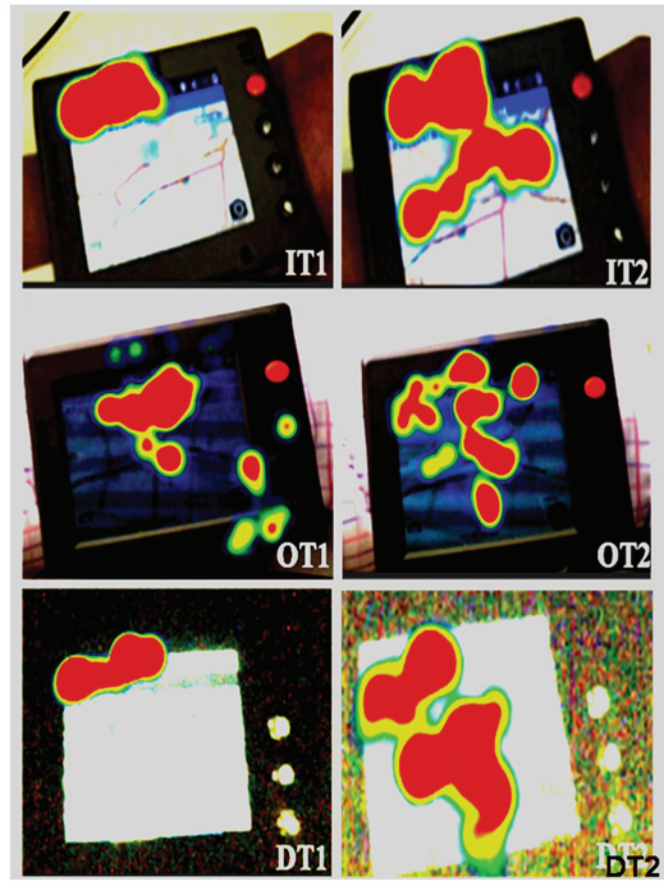
In the heatmap, a colour scale moving from blue to red indicated a gradually increasing focus of visual attention at a particular area of interest. More focused visual attention was observed at most of the important areas with pertinent visual sensory elements during completing desired reading tasks under indoor conditions compared to either Dark or Outdoor conditions (Fig. 6).

3.5 Scan path[26]

Visualisation of scan path (Fig. 7) during performances of T1 and T2 revealed that the indoor illumination condition facilitated maneuver in selecting an optimal scanning path in attending more relevant visual information from the area of interest with more number of fixation (Fig. 3) and less fixation duration (Fig. 4) as compared to dark and outdoor illumination conditions.

3.6 Focus Map[27]

The transparent portion of a focus map represented the exact area of focus and the rest of the area remained dark. It was observed that more visual attention was focused at the area



IT1- Indoor, Task 1; IT2- Indoor, task 2; OT1- Outdoor daylight, Task 1; OT2- Outdoor daylight, Task 2; DT1- Dark, Task 1; DT2- Dark, Task 2.

Figure 6. Visualisation of visual attention by Heatmap during task 1 and task 2 under different conditions of illuminations and font attributes while using WWC.

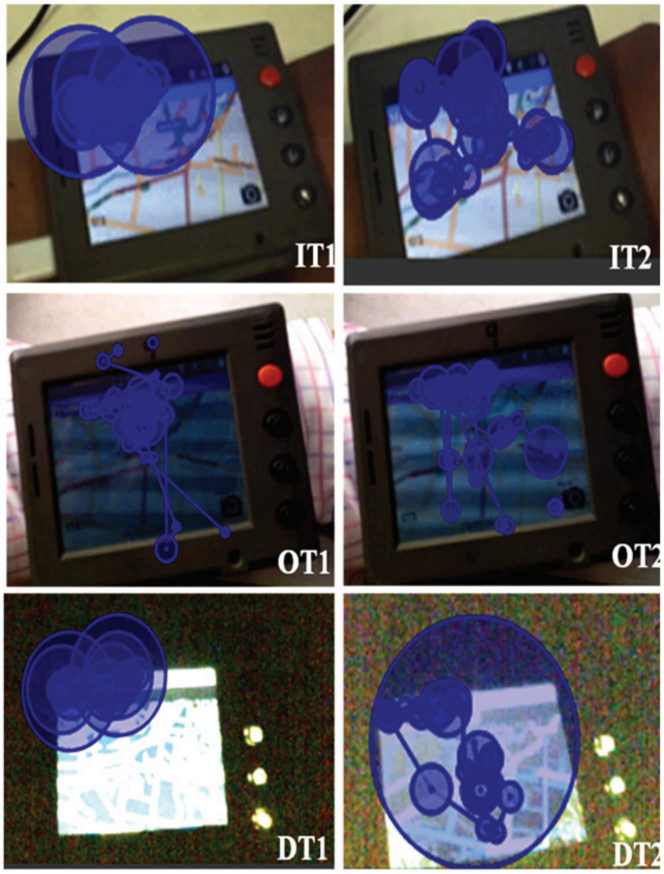
of relevant sensory visual inputs exactly for accomplishing the task successfully in indoor illumination conditions than dark and outdoor illumination conditions (Fig. 8). This indicated that less difficulty was experienced in extracting the sensory inputs from area of interest during performance of the task in indoor illumination condition.

3.7 Legibility Rating[17]

Participants reported legibility rating as 100 per cent satisfactory (passable and excellent) for both the tasks under indoor illumination conditions. However, under outdoor illumination condition 10 per cent, 20 per cent, 10 per cent and 30 per cent of population reported as unsatisfactory for SSLBT1, SSLBT2, SSHNT1 and SSHNT2 combinations, respectively. Similarly under dark illumination condition 10 per cent of population reported SSLBT2 combination as unsatisfactory (Table 4).

4. DISCUSSION

Present study was conducted to assess visual performance of an indigenously developed wrist wearable computer (WWC, Fig.1) with small size display across three different illumination conditions in terms of eye movement parameters and legibility ratings while performing some common tasks



IT1- Indoor, Task 1; IT2- Indoor, task 2; OT1- Outdoor daylight, Task 1; OT2- Outdoor daylight, Task 2; DT1- Dark, Task 1; DT2- Dark, Task 2

Figure 7. Visualisation of time spent on a particular area of interest by Scanpathduring task 1 and task 2 under different conditions of illuminations and font attributes while using WWC.

IT1- Indoor, Task 1; IT2- Indoor, task 2; OT1- Outdoor daylight, Task 1; OT2- Outdoor daylight, Task 2; DT1- Dark, Task 1; DT2- Dark, Task 2

Figure 8. Visualisation of focused visual attention on a particular area of interest during accomplishment of the tasks under different illumination conditions (focus map).

Table 4. Legibility rating as different percentage (%) of participant population

Illumination conditions	Indoor controlled			Outdoor			Indoor dark		
Tasks	U	P	E	U	P	E	U	P	E
SSLBT1	0	50	50	10	20	70	0	20	80
SSLBT2	0	40	60	20	10	70	10	0	90
SSHNT1	0	20	80	10	10	80	0	30	70
SSHNT2	0	20	80	30	10	60	0	30	70

U: Unsatisfactory; P: Passable; E: Excellent

(Fig.2). It was observed that visual task performance under indoor illumination condition was better than outdoor day light and dark illumination conditions.

For optimal performance under any operational environment, high contrast onscreen information display is needed. However, soldiers are required to operate in locations with varying lighting environment i.e. indoor, dark and bright outdoor. The wearable device used in the present study is meant for operation under varied illumination conditions. Reported studies on the effects of ambient illumination levels on visual performance while using small screen Wearable Computer to identify the optimised combination of display attributes are limited in literature and non-existent for Indian soldiers. It is important to understand the efficacy of WWC in terms of visual performance for minimizing error and establishing adequate communication under various operational situations of Command-Control-Communication-Computer Intelligence Surveillance and Reconnaissance (C^4ISR).Uniqueness of the current study lies in the fact that it is one of the earliest efforts made towards understanding visual performance of Indian soldiers while using WWC under operational conditions.

Previous study by Esposito (1997) reported that illumination and glare may appreciably affect reading from head mounted display[18]. The study by Lin and Huang (2009) reported that screen luminance was affected by ambient illumination intensity[3,19], causing screen image to fade[20] which in turn decreased luminance contrast with higher ambient illumination level[21]. Similarly, in current study, participants also faced difficulties due to glare and reflections while performing onscreen tasks under bright light outdoor ambient illumination. According to past studies, reporting eye movement responses, including both objective and visualisation techniques, were found to be effective in predicting visual performance with different monitors under various illumination conditions. Any change in ambient light intensity was associated with relevant change in screen luminance which was immediately perceived by the photosensitive cells in the retina, resulting in cortical presentation of altered display media.This in turn caused increased cognitive treatment of the sensory visual input between retina and visual cortex[22]. Previous studies have established that parameters like Fixation Profile[17,23-24], Scan Path Length[25] and visualisation techniques (Scanpath[26], Heat Map[26] and focus map[27]) had significant roles in describing visual performance for reading and searching tasks.

In the present context, information was displayed as combinations of Sans Serif-Large-Bold and Sans Serif-Huge-Normal with preferred screen brightness level for assessing visual performance. Findings of present study supported authors' hypothesis and showed that under indoor illumination condition participants performed better for all tasks as compared to outdoor daylight and indoor dark illumination conditions. This may be explained in terms of difference between illumination levels of surrounding and screen, which evoked a visual signal by activating respective photo-pigment cells in the retina andensured a smooth information transduction until the level of visual cortex and other important cortical areas, i.e., executo-frontal cortex. It can be postulated that under indoor condition, fixation duration at a specific point of fixation resulted in expected interpretation of information that ensured an optimal execution of relevant visuo-motor action. Thus, from the classical theory of vision, it can be stated that the indoor controlled, indoor dark and outdoor sunlight illuminations evoked a perception of vision similar to mesopic, scotopic and photopic vision, respectively[28].

The ever-changing surrounding of visual environment is characterised by the spectral, spatial and temporal properties of the illuminant. The human vision system is well equipped to perceive all these properties by switching the operations between rod and cone cells in order to achieve a maximum representation at the cortex. An outdoor bright light condition predominantly evokes photopic vision which is dominantly mediated by the cone cells while almost all the rod cells remained saturated or nonresponsive in mediating a visual transaction. Being mainly mediated by the cone cells, the day light/ bright light vision is characterised by high accuracy to acquire precise physical details of the objects like shape, size, colour, depth, etc. In contrast, the indoor dark illumination evokes scotopic vision, solely mediated by rod cells. When exposed to darkness, veryfew cone cells are activated, presenting poor visual cognition with difficulty in finding targets, ultimately resulting in increased mental workload. On the other hand, visual cognition under mesopic vision is critically achieved by the equal contributions from rod and cone cells. Almost all modern indoor lightings, outdoor night time recreational lighting, traffic lights, shopping mall and restaurant lightings, etc., present mesopic visual surrounding. The interactions between the rod-cone cells and the resultant signal transaction control almost every aspect of visual processing and detection[29-30], temporal vision[31-34], color vision[35-37], spatial vision[39], discrimination[39-40] and hue perception[41-42].

In the present study, participants had to accomplish their tasks by identifying visual elements on thesmall screen display of the WWC across three illumination conditions. However, the screen itself was an active source of light which emitted different wavelength corresponding to specific colour of the element. Therefore, irrespective of lighting conditions (i.e., photopic, scotopic and mesopic) the reading media was also an active source of light across all experimental conditions. Viewing under each experimental condition was influenced by combined illumination of surroundings and the screen, influencing the interpretation of observed results. Under such a circumstance, it was very difficult to predict whether the activation of the photoreceptors (rod/cone/rod-cone as per the lighting environment) was due to ambient illumination/ screen illumination/combined effect of both. It may be useful to postulate that the changes were influenced by a combined effect of surrounding and screen illumination. However, the contribution from either of the illumination type (surroundings/ screen) varied as per the level of the surrounding illumination. Hence, it may be stated that dark and outdoor daylight illumination conditions resulted in more contribution from screen illumination and ambient illumination, respectively. A brighter screen illumination under dark ambient illumination led to oversaturation of the rod cells resulting in poor dark adaptation causing suboptimal task performance. At the same time, different coloured bright light emitted from the screen caused activation of cone cells, making reading tasks easier under indoor dark illumination level despite dark surroundings. This is indicated by heat map(Fig. 6) and focus map (Fig. 8), where the responses under dark illumination were similar to that of indoor illumination condition. However, over longer duration of exposure, such illumination environment could generate visual fatigue owing to the perceptual conflict between dark surrounding and the bright screen. Further research is required to specifically separate out the extent of contribution by rod and cone cells under such experimental conditions. Likewise, a brighter surrounding in the outdoor ambient illumination during day time resulted in comparatively less bright screen which in turn resulted in fragmented focusing (Fig. 8) of visual attention despite the mediation through the activated cone cells. The indoor illumination condition offered a balanced contribution from surroundings and the screen resulting in an optimised visual performance.

The average illumination values of the screen under indoor, dark and outdoor daylight conditions measured were 35 lx, 6 lx and 245 lx, respectively. On the other hand, the average illumination values of surroundings under these conditions were 450 lx, 0.12 lx and 11818 lx, respectively, resulting in respective luminance differences of 415 lx, 5.88 lx and 11,573 lx. High level of luminance difference for outdoor daylight condition resulted in difficulties during onscreen reading, evident from fragmented visual attention.

Participants reported legibility rating as passable or excellent for indoor illumination under different display attribute combinations as opposed to 'unsatisfactory' legibility rating of 10 per cent, 20 per cent, 10 per cent and 30 per cent for SSLBT1, SSLBT2, SSHNT1 and SSHNT2, respectively, under outdoor illumination condition. Thus, subjective responses corroborated the reported eye movement responses in the present study.

It has been reported in literature that digital media like tablets and smart phones were important sources of high energy bright blue light with wavelength lying between 450-495nm. Excessive exposure to short wavelength light, particularly towards the ultraviolet range of the spectrum, may result in damaged photoreceptors and retinal pigment epithelium, glaucomatous changes in the ganglion cells[43], cataract[44] and predisposition to macular degeneration[45-46]. In the present context, under dark illumination condition the participants' eyes were exposed to the bright light emitted by the display of the wearable computer. Under real operational situations soldiers may be frequently exposed to dark environment for uncertain duration. During such exposures, their visual perception may getadversely affected due to long duration exposure to short wavelength bright light resulting in higher cognitive workload,reducing their combat efficiency and performance. Hence, further research efforts need to be targeted towards improvement of illumination properties of such displays for enhancing users' occupational safety and performance.

5. CONCLUSIONS

Present study may conclude that indoor illumination condition (average surrounding illumination of 450 lx and average screen illumination 35 lx) presented optimised illumination level for using the indigenously developed Wrist Wearable Computer by soldiers for communications.

However as the device is supposed to be used extensively for communication by soldiers under diverse illumination conditions during military operations, the luminance property of the screen needs to be improved for better viewing and reduced visual fatigue under bright daylight and dark illumination conditions. Further research is required to make the indigenous device versatile in terms of optimised visual performance under extremes of illumination conditions.

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