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Recognition efficiency of atypical cardiovascular readings on ECG devices through fogged goggles

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ABSTRACT

In their continuing battle against the COVID-19 pandemic, medical workers in hospitals worldwide need to wear safety glasses and goggles to protect their eyes from the possible transmission of the virus. However, they work for long hours and need to wear a mask and other personal protective equipment, which causes their protective eye wear to fog up. This fogging up of eye wear, in turn, has a substantial impact in the speed and accuracy of reading information on the interface of electrocardiogram (ECG) machines. To gain a better understanding of the extent of the impact, this study experimentally simulates the fogging of protective goggles when viewing the interface with three variables: the degree of fogging of the goggles, brightness of the screen, and color of the font of the cardiovascular readings. This experimental study on the target recognition of digital font is carried out by simulating the interface of an ECG machine and readability of the ECG machine with fogged eye wear. The experimental results indicate that the fogging of the lenses has a significant impact on the recognition speed and the degree of fogging has a significant correlation with the font color and brightness of the screen. With a reduction in screen brightness, its influence on recognition speed shows a v-shaped trend, and the response time is the shortest when the screen brightness is 150 cd/m². When eyewear is fogged, yellow and green font colors allow a quicker response with a higher accuracy. On the whole, the subjects show a better performance with the use of green font, but there are inconsistencies. In terms of the interaction among the three variables, the same results are also found and the same conclusion can be made accordingly. This research study can act as a reference for the interface design of medical equipment in events where medical staff wear protective eyewear for a long period of time.

1. Introduction

Electrocardiogram (ECG) machines are a commonly used electronic medical device for clinical diagnoses of heart abnormalities. They are used to assess heart rhythm, track cardiovascular health, or evaluate heart conditions after acute angina. Amidst the COVID-19 pandemic, ECG machines have an important role in tracking the heart health of patients with the virus, as severe COVID-19 patients may experience cardiac arrest. As such, medical staff who care and treat COVID-19 patients need to wear a complete set of personal protective equipment (PPE) which includes masks and protective eyewear, such as goggles, for long periods of time to reduce the risk of transmission [1,2]. However, the protective lenses of the goggles can fog up due to the difference between the body and the ambient temperatures as shown in Fig. 1, which tends to be more prevalent when one is perspiring as is the case with medical staff when they are wearing a mask and other PPE. The fogging of the lenses could very well lead to erroneous readings of information on ECG monitoring devices and impacts whether the information can be read accurately and quickly.

In similar situations where vision is impacted with reduced visibility, for instance, driving in dense fog, studies have found that light with a certain spectrum can penetrate fog better. The amount of penetration depends on the wavelength of the light [3]. Colors with short wavelengths, such as blue and violet, scatter more and are less visible to the eye. Conversely, colors with longer wavelengths scatter the least and penetrate through objects more strongly. The color with the longest wavelength is red [4]. Therefore, the color red universally conveys danger or serves as a warning of hazards, risk to life situations, or
Medical settings, it is worth discussing whether previous standards need higher vigilance performance [12]. This behavior can be explored through eye movement experiments [13]. However, the screen brightness affects the efficiency of recognizing information on the interface. When the screen brightness exceeds the brightness ratio threshold, visual fatigue will be caused and vigilance will be reduced [17]. As such, when designing an interface, the colors need to be determined with care, as it is an important means of increasing the recognition efficiency [27-30]. The use of colors should always have a purpose, and appropriate color combinations can ensure the effectiveness of a display and improve cognitive efficiency [31]. However, color can be culturally specific, and the wrong color used can lead to unpleasant misunderstandings [32]. In contrast to the other colors, the three primary colors (red, green and blue) facilitate a higher accuracy rate during tasks [33], with yellow font on a black background offering a higher degree of legibility as found in Wu et al. [34] and Huang [35]. Similarly, color variations can also improve search efficiency and reduce cognitive strain [36].

Previous research has mainly focused on the interface typography, such as the color and spacing of characters, and legibility, such as the contrast of the characters or icons with the background color. Aside from environmental illumination, there are practically no studies that have been done on other environmental factors that impact the deciphering of interface information. In addition, few studies have examined the interactive effects between screen brightness and font colors. To address this research gap, this article focuses on the impact of screen brightness and font color on search efficiency when medical workers are interpreting the numbers on an ECG display screen through fogged goggles. In addition, while some research has been carried out on warning alarms or messages on monitoring interfaces, and the influence of screen brightness and font color has been explored, this study extends their work and specifically focuses on the impact of fogged goggles on reaction time and the rate of accuracy of character recognition. In doing so, the encoding of interface information and recognition efficiency of the cardiovascular information on the ECG interface can be improved even while wearing fogged up goggles. The result would reduce mis-readings and consequently the likelihood of medical fatalities. In this study, a visual search experiment is used to investigate efficiency and accuracy while interpreting changing information on an ECG interface while wearing goggles with fogged lenses. The visual search experiment involves a simulated ECG interface, and is conducted using mental imagery to study the effects of a fogged up environment, screen brightness, and font color on recognition efficiency.

2. Experiment and method

2.1. Subjects

The recruitment of the subjects was done through an online survey. In total, 35 individuals in the School of Architecture and Design completed a survey and 30 graduate students who range from 21 to 26 years old were recruited as the sample after taking into consideration the inclusion criteria, including individuals with normal or corrected vision, and exclusion criteria, which is a diagnosis of color blindness or color weakness (minimum score of 20/40 as measured by a Snellen near acuity test). The recruited sample included 14 males (median age = 24.5 years old, standard deviation = 9.08) and 16 females (median age = 24.8 years old, standard deviation = 7.79). The subjects participated in a voluntary basis but received a notebook as a token of appreciation that is worth 5 dollars. Before the start of the experiment, the demographic information of the subjects was recorded, including their gender, age, study major, vision acuity and other relevant information. Subsequently, the experimental procedures were explained to them in detail. The experiment was approved by the ethics committee of the author’s university, and all of the participants provided written consent prior to participating in the study.

2.2. Experimental design

A single-task experiment was carried out which used a visual change detection paradigm and required the subjects to remember the search
target first, and then subsequently perform target recognition. The stimulus in the visual recognition was parameterized information of the cardiovascular system, including the various parameter names and Arabic numbers. Ten different digital stimuli were randomly presented, and the subjects had to identify the stimulus as quickly as possible. In order to control the influence of environmental illuminance on screen brightness, the national hospital lighting standard for wards of 100 lx was adopted. The ground was used as the reference point. A $3 \times 3 \times 4$ factorial design was used for the experiment, which considers the degree of fogging of the goggle lenses, screen brightness and font color to determine the recognition task efficiency in a short period of time. The first factor is the screen brightness, which has three levels (independent variables): $70 \text{ cd/m}^2$, $150 \text{ cd/m}^2$, and $350 \text{ cd/m}^2$. The screen brightness was measured by using a screen brightness tester (SM208 portable screen luminance meter with mini light detector) against a white background. The second factor is the font color. Three font colors (independent variables) are used: yellow, green, and blue. The third factor is the degree of fogging of the goggles. Three different levels of fogging are used, and unfogged goggles are used as the control (total of 4 factors). Based on these three dimensions of the initial item pool, the experiment was divided into 12 $(3 \times 4)$ trials which focused on screen brightness and degree of fogging of the goggles.

2.3. Stimuli

The stimuli were presented on a simulated ECG interface at a resolution of $1920 \times 1080$ px. The standard and simulated ECG interfaces are shown in Fig. 2. The parameter font is Arial, as shown in Fig. 3, and all the characters are 21 pt. Random cardiovascular values that range from 40 to 120 were used as the input, which were generated with Excel. The range of the normal cardiovascular values is 60–100. The ratio of the number of normal cardiovascular values and that of atypical cardiovascular values used in the experiment is 8:2 (in the oddball experimental paradigm, the probability of a deviation stimulus is usually about 20% and the probability of a standard stimulus is usually about 80%). The color standard is the RGB color mode. The RGB values of the three color variables are R:255 G:255B:0 for yellow, R:0 G:255B:0 for green, and R:0 G:255B:255 for blue. The RGB value of the black interface background is R:255 G:255B:255, while the brightness of these three colors is similar to that of the background under the same screen brightness, as shown in Fig. 4. In the simulated ECG interface, the parameter information related to the cardiovascular variable changes color along with the parameter.

2.4. Experimental equipment and procedures

The design of the experimental program is the same as that discussed in Ho et al. [37]. In this study, the response time and accuracy are examined. The experimental program was written by using E-Prime, a software used for behavioral research. The program was installed onto a computer with a CPU frequency of 2.7 GHz. The stimulus appeared on a 14-inch, 3:2 display with a screen resolution of $1920 \times 1080$ pixels. Normal lighting was used for the experimental conditions. In order to control the influence of the ambient illuminance on the screen brightness variables, a standard used for lighting hospital building, GB 50034–2004 Standard for lighting design of buildings, was adopted. The ground is the reference point and the illuminance value is 100 lx. A scale with three values was used to depict the changes in the degree of blurring or level of foggingness based on the three experimental variables, which are 7, 9, and 11, while the highest degree of fogging of the goggle lenses is given a value of 120. The fogging of the surface of the lenses is simulated by applying an obscuring sticker, as shown in Fig. 5. Images of the blurred view of the interface were taken by using a camera placed 3 cm behind the goggle lenses, as shown in Fig. 6. The resultant images are shown in Fig. 7. A Python language program, OpenCV, was used to calculate the Laplacian operator: cv2.Laplacian(image, cv2.CV_64F).var()

After the target (parameterized information and Arabic numbers) was presented to each subject, they were instructed to immediately press the “F” button on the keyboard. Each subject would repeat this 5 times. Then E-Prime recorded the reaction time and calculated the average reaction time, which is 1030 ms (standard deviation = 304 mm). The gaze time of the identified target was set to 3000 ms. Prior to the formal start of the experiment, a preliminary experiment was first conducted, which is the same as the formal experiment, to allow the subjects to gain familiarity and proficiency with the task to reduce any reaction time errors caused by the difference in proficiency during the experiment; see Fig. 8.

In the formal experiment, the subjects first read the instructions for the experiment, and then were instructed to press any key on the keyboard to start the experiment. The subjects were to first place the “+” sign onto the center of the screen as the central fixation point for 500 ms, and then the object for the target recognition task was presented to the subject. After the subject looked at the stimulus, s/he assessed whether the cardiovascular value shown on the ECG machine is a normal value, and if so, pressed the “F” key (that is; the range of the normal cardiovascular value is 60–100). If the reading is abnormal (i.e., cardiovascular value < 60 or > 100), the subject pressed the “J” key. After pressing the F or J key, the stimulus disappeared. Then, after an onset

Fig. 2. Interface of standard and simulated ECG interfaces.

Fig. 3. Font selection.

Fig. 4. Color selection.

Fig. 5. Goggles with different degrees of fogginess.
3. Results

3.1. Reaction time and percentage of accuracy of each variable under different degrees of fogging

After excluding outliers, a statistical analysis was conducted for the response time and rate of accuracy. A one-way analysis of variance (ANOVA) was carried out for each independent variable (or the level in the factorial experiment), and the calculated mean and standard deviation are shown in Table 1. A statistical software, Statistical Package of Social Science (SPSS), was used to conduct a multivariate analysis of variance (MANOVA). The results are shown in Table 2, where F represents the significant difference level, and P represents the significance level of the test [38]. With reaction time as the dependent variable, it can be observed that the font color (F = 9.737, p = 0.002 < 0.01) and the degree of fogging (F = 29.148, p = 0.000 < 0.01) have very significant effects. The effect of the screen brightness (F = 3.192, p = 0.048 < 0.05) is weakly statistically significant. In terms of the effect of the interactions, the effect of the interaction between the degree of fogging and font color (F = 2.986, p = 0.021 < 0.05) is significant, and that among screen brightness, font color and degree of fogging (F = 2.986, P = 0.011 < 0.05) is also significant. However, no significant interaction can be found among the other factors. The result shows that when accuracy is the dependent variable, the degree of fogging (F = 10.013, p = 0.000 < 0.01) has a very significant impact. The influence of font color (F = 5.693, p = 0.016 < 0.05) is somewhat more significant, while that of screen brightness (F = 2.366, p = 0.130 < 0.05) is not significant. The effect of the interaction between the degree of fogging and font color (F = 2.529, p = 0.035 < 0.05) is more significant. The effect of the interaction among the other variables is not significant. Since the ECG interface is being simulated in this experiment, the experimental conditions reflect its real-life usage including limiting the time to view the stimuli and increasing the cognitive load of the subjects. As such, the study results can be used for reference purposes.

3.2. Effect of screen brightness on response time

Since the influence of screen brightness on the reaction time has no significant interaction with other factors, an ANOVA was performed on screen brightness, as shown in Fig. 10. The result shows that when the brightness is 150 cd/m2, the response time is the shortest (mean = 743 ms). The response time is the longest when the screen brightness is 50 cd/m2 (mean = 863 ms), and the response time is moderate at the highest screen brightness.

3.3. Interactive influence of font color and degree of fogging

In terms of the response time and accuracy, the font color and degree of fogging appear to be correlated. This means that there is a difference in the level of response between changes in fogginess with font color, which shows that the effect of the degree of fogginess and the color of the font is not independent of each other. Taking the reaction time as the dependent variable, the reaction time to different colors differs with variations in degree of fogginess. As shown in Fig. 11, the average reaction time shows an upward trend, thus indicating that more fogged up lenses increase the reaction time. The fastest response time (mean = 695 ms) can be observed when the degree of fogging is 11 and the color of the font is yellow. The slowest response time is observed when the degree of fogging is 7 and the color of the font is blue (mean = 968 ms). The results show that for all the different physicochemical parameters, a blue color font results in the slowest response. The response time when viewing a yellow font at a level of fogginess that does not exceed 9 is faster than viewing a green font. However, when there is a large amount of fogging, the response time when viewing a yellow font is greatly increased, and in the end, exceeds that of the green font. Taking the rate of accuracy as the dependent variable, as shown in Fig. 12, it can be
concluded that as the level of fogginess increases, the accuracy of any of the font colors shows a downward trend. However, the rate of accuracy with the yellow font is the highest (mean = 0.948) when the degree of fogging is 11. Although the highest accuracy rate is found when the yellow font is used, this rate also fluctuates greatly. The accuracy rate is the lowest at fogging levels of 9 and 120, and the accuracy rate is second only to blue when the degree of fogging is 7. The green font allows the viewer to provide a relatively stable performance within the different degrees of fogginess, and the accuracy rate is around 0.9, and even the highest when the lenses are very fogged up at a level of 9 (mean = 0.906) and 120 (mean = 0.917). The overall accuracy rate when using a blue font is always low, and the accuracy rate even deteriorates to the lowest value at a fogginess of 7 (mean = 0.667).

3.4. Interactions among font color, screen brightness and degree of fogging

The effect of the interactions among font color, screen brightness and degree of fogging on the reaction time is shown in Fig. 13. Since the interactions among these three factors are more complicated, the focus here is mainly on how they can improve the recognition efficiency in a fogged environment. A degree of fogginess of 7 along with a screen brightness of 50 cd/m² consists of a very extreme environment and would affect the surrounding environment anyway, and as such, will not be further elaborated. When the degree of fogging is 11, the screen brightness is 350 cd/m², and color of the font is yellow, the recognition rate is the fastest (mean = 642). However, when the degree of fogging is 9, the recognition rate will be reduced (mean = 734). At this time, the recognition efficiency of the green font with a brightness of 150 cd/m² is the highest (mean = 665). Finally, when the degree of fogging is 11, the recognition efficiency is still relatively fast (mean = 671). The recognition efficiency is the poorest with a blue font color and brightness of 350 cd/m² even when the lenses are not fogged up (mean = 633), but

![Fig. 9. Experimental process.](image)

![Fig. 10. ANOVA results: Screen brightness.](image)

### Table 1
Mean and standard deviations of reaction time and rate of accuracy based on the independent variables.

| Independent variable | Reaction time (ms) | Rate of accuracy (%) |
|----------------------|--------------------|----------------------|
|                       | Mean               | Std. Error           | Mean               | Std. Error |
| Level of fogginess (LF) |                    |                      |                    |            |
| 7                    | 951.57             | 42.828               | 0.770              | 0.019      |
| 9                    | 793.78             | 27.916               | 0.872              | 0.016      |
| 11                   | 741.56             | 26.974               | 0.905              | 0.016      |
| 120                  | 721.84             | 29.657               | 0.886              | 0.015      |
| Color (C)            |                    |                      |                    |            |
| Green                | 800.57             | 33.225               | 0.871              | 0.017      |
| Yellow               | 790.08             | 33.360               | 0.835              | 0.019      |
| Blue                 | 816.49             | 34.518               | 0.870              | 0.016      |
| Brightness (L)       |                    |                      |                    |            |
| 70 cd/m²             | 863.86             | 40.821               | 0.831              | 0.019      |
| 150 cd/m²            | 743.06             | 27.102               | 0.859              | 0.017      |
| 350 cd/m²            | 767.38             | 30.725               | 0.883              | 0.016      |

### Table 2
MANOVA results of reaction time and rate of accuracy.

| Effect          | F      | Df   | Sig.  | Eta Squared |
|-----------------|--------|------|-------|-------------|
| Reaction time   |        |      |       |             |
| LF              | 29.148 | 3.00 | 0.000 | 0.726       |
| C               | 9.737  | 2.00 | 0.002 | 0.364       |
| L               | 3.319  | 2.00 | 0.048 | 0.163       |
| LF*C            | 2.986  | 6.00 | 0.021 | 0.374       |
| LF*L            | 0.350  | 6.00 | 0.904 | 0.065       |
| C*L             | 0.675  | 4.00 | 0.614 | 0.078       |
| LF*C*L          | 2.986  | 12.00| 0.011 | 0.599       |
| Rate of accuracy|        |      |       |             |
| LF              | 10.013 | 3.00 | 0.000 | 0.589       |
| C               | 5.693  | 2.00 | 0.016 | 0.449       |
| L               | 2.366  | 2.00 | 0.130 | 0.253       |
| LF*C            | 2.529  | 6.00 | 0.035 | 0.265       |
| LF*L            | 0.342  | 6.00 | 0.911 | 0.047       |
| C*L             | 0.259  | 4.00 | 0.902 | 0.036       |
| LF*C*L          | 1.349  | 12.00| 0.207 | 0.162       |
when the lenses start to fog up or the brightness is reduced, the reaction time is significantly higher.

4. Discussion

The purpose of this study is to examine the effect of character coding on ECG interfaces on the recognition efficiency of medical staff who wear goggles for a long period of time. This long duration of wear may cause the lenses to fog up. Therefore, the coding is enhanced to reduce the response time and risk of making errors. In the experiment, the degree of fogging of the lenses, screen brightness and font color, and their interactions are examined. As far as the screen brightness is concerned, the experimental results show that the subjects have a better visual performance under a moderately bright screen (150 cd/m²), and are most cognitively alert and efficient in recognizing atypical cardiovascular readings. The results differ from those of Buchner et al. [39] and bin Zaini et al. [4] who showed that high levels of screen brightness enhance visual performance and proofreading task performance. The difference in the findings might be due to the different types of tasks carried out by the subjects during the experiment. This study mainly focuses on the efficiency of reading atypical values, that is, we examine the level of alertness of the subjects who are confronted with atypical information during routine readings. Previous studies have mainly used search tasks. The glare and visual fatigue caused by a highly illuminated screen [40,41] may have a detrimental impact on the results of this study. Another divergence from previous studies is that the experimental component of this study is carried out with fogged up goggles. Viewing a very bright screen through fogged up lenses is more likely to cause glare and visual fatigue, which will affect the experimental results. This means that when medical workers need to wear goggles for a long period of time, a highly illuminated screen may increase their response time. Therefore, a moderately bright screen can ensure a more timely response. When there are conflicting factors that are impactful, certain specifications need to be made in the design of the interface. For example, ISO 9241–303 (2011) recommends that when the horizontal illuminance is 500 lx, the brightness of the screen should fall within the range of 100–150 cd/m². Similarly, the brightness of the screen when viewed through fogged up lenses can be standardized. As for the influence of the font color, yellow and green fonts encourage a better performance under different degrees of fogging, and the overall recognition efficiency of yellow font under different levels of brightness is relatively high even though the error rate fluctuates greatly. Nevertheless, with a brightness of 150 cd/m² as discussed above, green font provides better results than yellow and blue fonts. This is inconsistent with previous research results. Luria et al. [42] and Al-Harkan and Ramadan [43] both found significant differences in the impact of different font colors on the error rate. The former indicated that yellow target letters on a dark background produce the fewest errors while the latter found that green is more superior unless the character contains a square. Shieh and Chen [44] found that blue and black backgrounds allow for better cognitive efficiency. The reason for the difference between the results of previous research and those of this research study may be that yellow and blue could have better legibility, but the subjects are not sensitive to these two colors, and the experiment is carried out in a fogged environment. Green light penetrates fog more readily than blue because it has a higher wavelength and excels the penetration ability of yellow. Of course, the difference between yellow and green is not significant, but yellow is weakly correlated with different fogged conditions and screen brightness. Therefore, it is recommended that when wearing goggles for a long period of time which causes the lenses to fog up, medical equipment should use green for interface codes to reduce the error rate and increase alertness. As far as the degree of fogginess of the lenses is concerned, the experimental results show that more fogged up lenses reduce the
reaction rate and increase the error rate. In addition, the environmental variable of fogged lenses has a significantly interactive effect on both screen brightness and font color, and yellow characters elicit the shortest response time. The reason for discrepancy between the results of this study and those in the literature is due to the different colors that can penetrate fog. Takamatsu and Nakas [45] and Kurniawan et al. [46] experimentally proved that yellow light provides good visibility in fog with different droplet diameters and densities. They also found that blue light provides the least amount of visibility. The influence of fogged up lenses on the cognitive efficiency of reading information on an ECG interface has been validated in this study. The effects of font color and screen brightness on recognition efficiency and accuracy when wearing protective goggles are worn for long periods of time, that is, during pandemics.

Fig. 13. Interaction among font color, degree of fogging of the goggles and screen brightness in terms of reaction time.

As with all studies, this study has some limitations which prevent generalizability. The subjects in this study are mainly students between 21 and 26 years old. It would be interesting if other age ranges, involvement of professional medical staff in the experiment, and use of electrocardiographs to evaluate their visual recognition efficiency.

In order to simplify the results, this study only examines the influence of screen brightness and font color which might produce less than accurate results. In order to increase the robustness of the results, the brightness interval might be reduced and the hue and color temperature in future research. Color saturation and other color changes should also be taken into consideration.

The main purpose of this research work is to explore the impact of complex environments on high-load cognitive processes. However, the actual environment cannot be replicated due to limitations in the experimental conditions, nor can the study fully explore all of the interface elements, such as the time and task pressures found in medical scenarios; different viewed angles when medical workers read electrocardiographs; and environmental factors, such as movement or shaking during emergency treatment. Moreover, other interface typography has been neglected, such as font spacing, size and brightness, and reminders on the interface when abnormal readings arise. A more comprehensive exploration of the impact of complex environments on high-load cognitive tasks so as to provide the theoretical basis for more efficient and accurate treatment of patients under pandemic conditions is recommended which will be ‘left for future work.

5. Conclusion

This study uses an analog ECG interface to carry out visual target recognition experiments with digital font. Variables include the font color, brightness of the device screen, and degree of fogging of the protective goggles. The interactions among these three variables have significant impacts on recognition efficiency. Green is recommended as the font color for ECGs with a screen brightness of 150 cd/m² if protective goggles are worn for a low error rate, consistency in reading the information, and the fastest response time. With increased fogging and therefore less visibility, the recognition efficiency of digital characters is significantly reduced. Therefore, appropriately reducing the display brightness of an ECG device and using green as the font color while viewing the interface with fogged up glasses will enhance the efficiency of reading the digital information. The findings in this study can be used to guide the interface design of medical equipment if protective glasses are worn for long periods of time, that is, during epidemics and pandemics.

CRediT authorship contribution statement

Jia-Wei Ren: Methodology, Conceptualization, Data curation, Resources, Writing – original draft, Supervision, Funding acquisition. Jun Yao: Methodology, Software, Validation, Formal analysis, Writing – review & editing, Visualization. Ju Wang: Project administration, Investigation. Hao-Yun Jiang: Software, Formal analysis, Investigation. Xue-Cheng Zhao: Investigation, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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