The following publication F. Li et al., "Usability Evaluation of Hybrid 2D-3D Visualization Tools in Basic Air Traffic Control Operations," 2021 IEEE International Conference on Systems, Man, and Cybernetics (SMC), 2021, pp. 3367-3372 is available at https://dx.doi.org/10.1109/SMC52423.2021.9658807

Usability Evaluation of Hybrid 2D-3D Visualization Tools in Basic Air Traffic Control Operations*

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Abstract—**Nowadays, increasing attention has been drawn to hybrid 2D-3D visualization tools, while evaluating them with a convenient and objective tool has only been carried out in a small number of areas. In this study, a revised radar chart-based usability evaluation approach was proposed. The approach was adopted to evaluate the hybrid 2D-3D radar display in air traffic management. The holding stack in air traffic management is analyzed and simulated, two generic tasks are designed accordingly. The hybrid 2D-3D radar display settings are evaluated based on six indicators from eye-tracking and brain dynamics data, namely, the frequency of fixation, fixation mean duration, fixation time on an area of interest, emotion, workload, and stress. The results reveal that the hybrid 2D-3D radar display induces spatial memory loss and high workload, while requires a shorter fixation duration.**

I. Introduction

The primary role of Air Traffic Control Officers (ATCOs) is to guide and direct air traffic flow. They are presented with vast amount of flight data daily and they must make timely decisions after processing these data. Normally, the role of ATCO can be divided into three main categories – area control, approach, and aerodrome control. While each category governs a phase of a regular plane's flight path, the workload is dependent on the number of flights within their jurisdiction [1]. With the increase in global air travels [2], it is highly likely that the workload on ATCO would increase.

Though there are technologies invested in automating certain aspects of the ATCO's roles [3], there will still be specific roles that would be taken by ATCO, such as intervening during failure of automated aircraft systems or during adverse weather. Hence, to aid ATCO, the hybrid 2D-3D visualization was conceptualized. The dual orientation involves two screens, one presents 2-Dimensional (2D) data and another with a 3-Dimensional (3D) data visualization. This dual orientation is to exploit the advantages attached to either orientation. Both 2D and 3D displays are useful for analyzing 3D spatial data [4]. This concept does not aim to completely replace 2D data visualization with 3D data visualization, given the benefits that are associated with 2D display.

The shortfall of 2D data visualization comes with difficulty in a mental visualization of a 3D space, a skill needed in air traffic management operations. Moreover, there might be an overlap of data points when two planes fly over one another on a 2D data visualization. Having an additional 3D display may remove these difficulties as it provides a 3D representation of the data [1]. Previous studies have established that ATCOs could benefit from having a dual orientation system during Holding Stack Management, including a reduction of stress and an improvement in performance [4]. However, there were no specific attempts to examine concerns such as spatial memory loss and visual search efficiency loss that caused by switching between hybrid displays.

Any losses in spatial memory would have an adverse impact given the high intensity in air traffic control (ATC) [5]. This loss in spatial memory may occur when ATCOs transit between 2D display to 3D display, or vice versa. Nevertheless, the existed research experiments were conducted in either a 2D or 3D display setting, with no specific attempts to evaluate the effects of a dual orientation system on spatial memory.

This study dives deeper into core principles to evaluate the potential drawbacks of having dual orientation system in three main aspects - potential loss in spatial memory, loss in visual search efficiency, and increased mental workload owing to the transition between the dual orientation system. These hypotheses were tested using electroencephalogram (EEG) and visual tracking methodology.

Normally, the statistical analysis will be conducted to compare the three aspects [1]. Nevertheless, considering the multidimensional aspects, how to generate a final evaluation from an overall perspective is challenging. To address this problem, a radar chart-based method is proposed to well handle the statistical analysis results of multisource data and to provide a final evaluation from an overall perspective.

The paper is organized as follows: Section II presented a literature review on air traffic control operations, 2D & 3D data visualization, electroencephalography, and eye-tracking. The details of the proposed radar-chart-based usability evaluation method are discussed in Section III. Section IV presents experimental results and a short discussion. Section V concludes the study with the contributions, limitations, and future works.

II. Literature review

A. Air traffic control

The modern air traffic control workstation typically comprises of a Flight Radar Display (FRD) and a Flight

*Research supported by the National Research Foundation, Singapore.

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Information Display (FID). There could be more screens providing ATCOs with additional information, such as weather displays and aeronautical charts [2]. Nowadys, the visualization of data is generally in a 2D orientation. Aircrafts are represented by dots, with data call outs including aircraft call-signs, flight levels, and other aircraft data.

An ATCO could experience difficulties in visualizing aircraft flying on different altitudes as all data are displayed on the same plane. The only point for reference for ATCO is the numerical flight labels attached to each aircraft symbols. Studies have concluded that ATCOs experience difficulties in visualizing aircraft altitude behavior as well as vertical separation with only 2D orientation system [6].

B. 2D and 3D Visualization

2D orientation means that icons are shown in a 2D plane, in an X-Y space with attached parameters, such as velocity, displacement, and altitude of an aircraft. Advantages of 2D displays include:

- Faster visual searches for air control displays [7]
- Similar if not superior capabilities in displaying altitude and speed judgement [7]
- Useful for seeing details of a particular part or measuring one-dimension distances [8]

Similarly, 3D orientation is a form of visualization in a 3D space, where icons are displayed in an X-Y-Z space with attached parameters. Some possible advantages of having a 3D display includes:

- Displaying large sets of data points [9]
- Improving user's spatial performances [9]
- Enhancing of user's capabilities in collision avoidance tasks [7]
- Gaining an overview of a 3D space [10]

Though a 2D orientation has some disadvantages, ATCOs are familiar with it, and it has a long application history in air traffic control operations. While 3D orientation promises to provide some benefits over the use of the 2D orientation, the slow uptake of this orientation suggests some underlying distrusts in applying a 3D orientation. Studies have shown that a 3D orientation system could cause distortions to the user's perception, raising a concern in "precise spatial assessment" for 3D orientation system [11]. In addition, there is difficulty in establishing the best perspective to view a 3D model, as the perspective is orientated to suit the task [10]. There lie the issues, where a lack of standardization serves as an outlier in an otherwise highly regulated environment in ATC.

C. Electroencephalography

Electroencephalography (EEG) is a medical imaging technique that reads scalp electrical activities generated by brain structures [12]. As the brain is the primary location that processes external stimuli and generates the appropriate bodily responses, measuring brain activities constitutes one of the common ways to quantify physiological states, such as emotion, workload, and stress. In the measurement of brain activities, the electroencephalogram is by far the most studied and accepted form of measurement [13].

Traditionally, EEG measurements made by the electroencephalogram produce sinusoidal wave shapes ranging from 0.5 to 100 μV in amplitude [12]. EEG signals normally include power spectra of several distinct frequency bands, such as delta, theta, alpha, and gamma [13]. The correlations between cognitive states and EEG signals have been confirmed in many studies [14]. Lim et. al [15] developed an algorithm from investigating EEG data processed and analyzed using power, statistical, fractal dimension (FD) features with Support Vector Machine (SVM) and k-Nearest Neighbors (k-NN) classifiers. The study proposed a combination of statistical and FD features in the algorithm which produced the most accurate results.

EEG has been widely used to assess human factors issues, such as workload, fatigue, stress, vigilance, and situation awareness, and user preference [13]. A study proposed a compact and interpretable Convolutional Neural Network (CNN) to discover shared EEG features across different subjects for driver drowsiness detection [16].

In this study, EEG is applied to measure the subjects' emotion, stress, and workload during the utilization of the hybrid 2D-3D radar display in air traffic management. The three mental states are selected as evaluating indicators as they have long been found to be highly associated with interface usability [3]. The emotion presents the satisfaction level of users, workload and stress indicate the difference between system requirement and users' ability.

D. Eye-tracking

Eye tracking is the process of acquiring the information corresponding to the eye movements, containing both spatial information and temporal information [17]. It has been utilized in numerous research projects, such as detection of road signs [18], route planning [19], and extraction of learning materials [20]. By examining different parameters involved in oculomotor behaviors, various information on conscious and subconscious behavior could be obtained [21]. Normally the following eye-tracking-based parameters are used to evaluating data visualization interface.

Fixation count refers to the total number of times a subject fixates one's gaze on area of interest (AOI) [22]. It indicates information processing, where an increase in complexity in processing information would result in higher fixation counts [23][24]. In comparison to the number of AOI fixations, saccades are also counted as a visit, adding an additional layer. It serves as an attention measure, which gives a viewpoint on early and late processing [25]. An increase in the number of AOI visits provides a similar viewpoint as AOI fixation. Fixation duration is used as a measure of dynamic visual memory load [22]. While both average fixation duration and pupil's size could be used as an indication for dynamic memory load, it has been observed that average fixation duration is a better indicator, as it reflects the mental workload both within and outside of the working memory capacity limit [26]. An increase in fixation duration corresponds to an increase in memory load.

In this study, three eye-tracking parameters, namely the frequency of fixation, fixation mean duration, fixation time on an area of interest are selected as evaluating indicators. As mentioned above, the three parameters have close relations with interface usability. In addition, they can be easily calculated and can be collected by the eye tracker with a low-frequency sampling rate.

III. METHODS

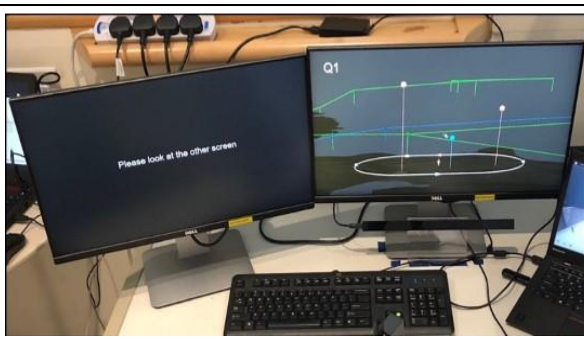
A. Participants

The study involved 20 students, majoring in aerospace and aeronautical engineering. The subjects had a demographics split of 10 females and 10 males, all of whom belonged in the age group of 20 to 30 years old. This research was approved by the Institutional Review Board of Nanyang Technological University (NTU-IRB), Singapore (IRB-2015-08-009). All methods were carried out in accordance with the guidelines and regulations of NTU-IRB. All subjects signed the informed consent form before participating in the experiment.

B. Experiment procedures

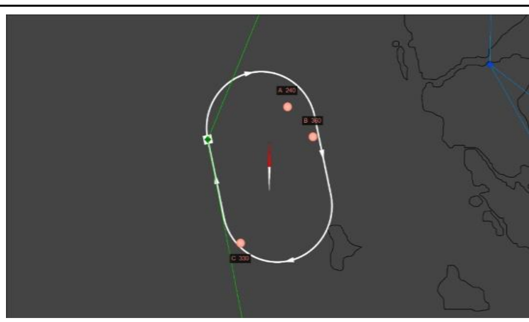
The Tobii pro glasses 2 with a 50 Hz sampling rate and the EMOTIV EPOC+ Headset with 128 Hz sampling rate were used in this study. Two displays were utilized in this study, as shown in Fig. 1. Both of them can display 2D and 3D orientations. Fig. 2 and Fig. 3 show an example of a 2D visualization and a 3D visualization of data, respectively. The experiment is designed based on holding stack management, which is a common and critical ATC operation. Hence, the interface was designed to show various aircraft in a simulated holding stack, with a white racetrack pattern displayed on the bottom for a visual reference. The flight label includes the aircraft's callsign and altitude, using the format of a letter followed by a number.

Figure 1. Dual-display monitor set-up



Two generic tasks are proposed based on holding stack management, a common task in ATC operations.

Figure 2. Example of 2D orientation visualization of data



- Task 1: Select the dot based on their callsigns in alphabetical order (A =>B =>C =>D).
- Task 2: Two dots are highlighted in yellow. Select the dot at a higher altitude.

The two questions were designed to simulate visual search and relative position tasks, which are two most common tasks in holding stack management. A with-in subject experiment was designed, with the dual-display settings (2D=>2D, 3D=>2D, 3D=>3D, 2D=>3D) as independent variables. Within each dual-display setting, fifteen (15) trials were run. On each trial, subjects were required to complete task 1 and 2.

The AOI was created in Tobii Pro Lab with the following considerations: first, each AOI is of the same size, and are represented by circles with a box height and width of 250px; and each AOI was placed in the center of the visual target.

The study took an average of 2 hours, which included the following tasks,

- Set-up of simulator and hardware
- Experiment briefing to subject
- Calibration of EEG and eye tracking devices
- Training on simulator
- Conduct of experiment
- Completion of questionnaires
- Debrief and remuneration to participants.

C. Radar chart-based usability evaluation

Six features were generated from the EEG and eye-tracking data to evaluate the hybrid visualization system. First, the CogniMeter was adopted to process the EEG data and collected three features, namely emotion, workload, and stress [27]. Three features of eye movements, namely the frequency of fixation, fixation mean duration, and fixation time on an AOI were collected based on I-VT method [24].

Mean values and standard deviations (SD) are calculated for all the six features. Analysis of variance (ANOVA) is conducted. Mauchly's test of sphericity was conducted to check the assumption of sphericity. Sphericity is assumed if Sig. >0.05. If sphericity is very badly violated, the multivariate test results are adopted. If the obtained p value of the specific feature (F) is less than 0.05, the feature is significantly affected by the information visualization tools. To make the results of evaluation to be easily understand, the radar chart is adopted in this study. Instead of using the traditional radar chart, the study proposed to consider the ANOVA results in drawing the radar chart. Specifically, the values used in the radar chart are the reciprocal of ranks instead of the statistical mean values. The rules of generating the ranks are as follows:

First, for all the six features, except emotion, the information visualization tool i ranks before the information visualization tool j, only if $F_i < F_j$ and p of ANOVA is lower than 0.05, as presented by Eq. (1):

$$R_i < R_j, \text{ if } \quad F_i > F_j \quad \text{and} \quad p < 0.05 \qquad (1)$$

Second, for emotion, the information visualization tool *i* ranks before the information visualization tool *j*, only if $F_i > F_j$ and *p* of ANOVA is lower than 0.05, as presented by Eq. (2):

$$R_i > R_j, \textit{ if } \quad F_i > F_j \quad \textit{and} \quad p < 0.05 \tag{2}$$

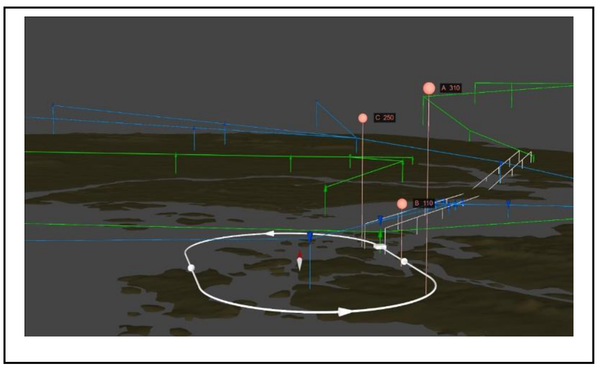
Third, the information visualization tool *i* and the information visualization tool *j* have the same rank if *p* of ANOVA is higher than 0.05, as presented by Eq. (3):

$$R_i = R_j, \textit{ if } p > 0.05 \tag{3}$$

R_i refers to the rank of the information visualization tool *i;* the *i, j* refers to the index of the information visualization tools.

The radar chart is drawn based on the reciprocal of ranks instead of the statistical mean values, as the mean values can easily be affected by variances. The coverage of the radar chart can be calculated to generate the final usability evaluation.

Figure 3. Example of 3D orientation visualization



IV. Results

A. Results of Eye-tracking and EEG indicators

The eye-tracking data and EEG data were processed by filtering and deleting. Eye-tracking data from five subjects and EEG data from four subjects were deleted due to the loss of track or large number of noises. Thus, eye-tracking data of 15 subjects were analyzed and EEG data of 16 subjects were analyzed.

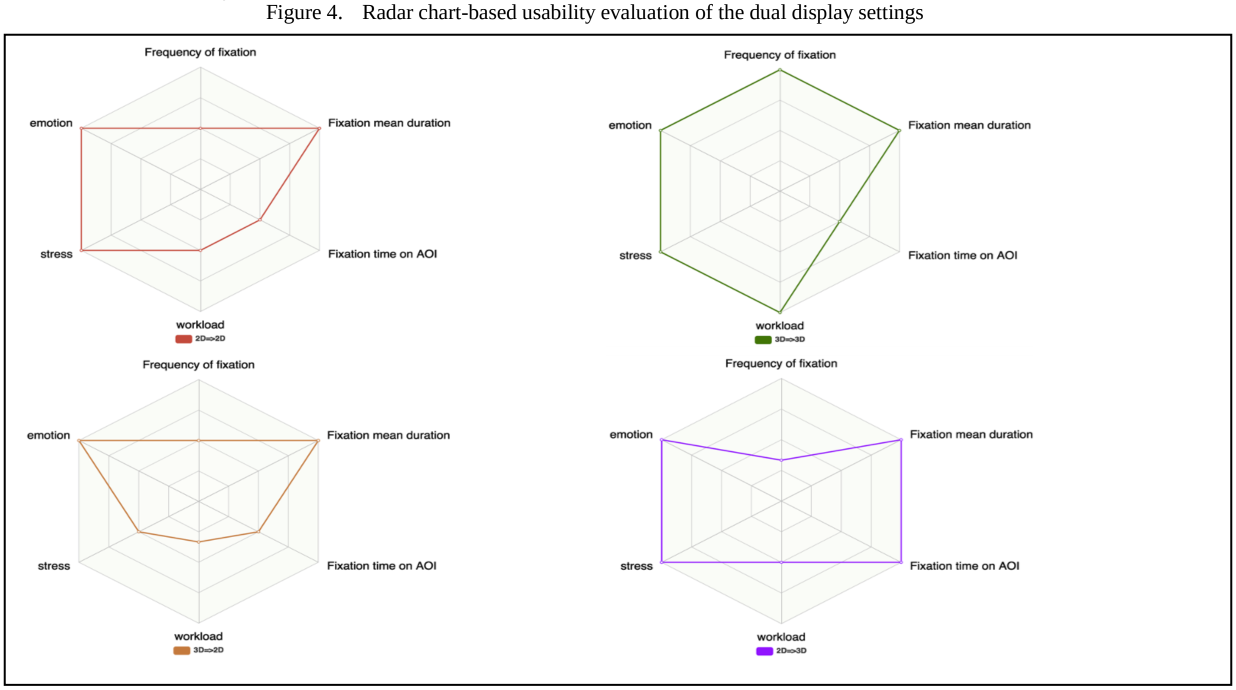
- *Frequency of fixation:* Significant differences between the dual-display settings were found on the frequency of fixation, $F_{(3,42} = 6.523$, $p = 0.001$, $n^2 = 0.318$. The post hoc analysis revealed the least number of visits of 3D=>3D (mean = 1.495, SD = 0.05) than 3D=>2D (mean = 1.824, SD = 0.091), 2D=>2D (mean = 1.617, SD = 0.057), and 2D=>3D (mean = 1.694, SD = 0.082). Moreover, the 2D=>3D showed significantly more visits in the right display than 2D=>2D and 3D=>3D.

- *Fixation mean duration:* No significant differences between the dual-display settings were found on the fixation mean duration, $F_{(3,42)} = 0.584$, $p = 0.629$.

- *Fixation time on AOI:* Significant differences between the dual-display settings were found on the Fixation time on AOI, $F_{(3,42)} = 3.431$, $p = 0.025$, $n^2 = 0.179$. The post hoc analysis revealed the shortest average visit duration in 2D =>3D (mean = 0.471s, SD = 0.037), which differed significantly from 3D=>2D (mean = 0.545s, SD = 0.046), 3D=>3D (mean = 0.524, SD = 0.043), 2D=>2D (mean = 0.559s, SD = 0.058). No significant difference was observed between 3D=>3D, 2D=>2D, and 3D=>2D.

- *Workload:* For mental workload, there was a significant difference between the dual-display settings, $F_{(3,45)} = 7.645$, $p = 0.003 < 0.05$, $n^2 = 0.638$. The post hoc analysis revealed that participants showed the lowest workload in 3D=>3D (mean = 3.406, SD = 0.406), and the highest workload in 3D=>2D (mean = 4.813, SD = 0.476). No significant difference in the workload level was observed between 2D=>2D (mean = 4.188, SD = 0.465) and 2D=>3D (mean = 3.844, SD = 0.449).

Figure 4. Radar chart-based usability evaluation of the dual display settings



- *Stress:* A significant effect of the dual-display on the stress was observed, $F_{(3,45)} = 8.025$, $p = 0.000 < 0.001$, $n^2 = 0.349$. The post hoc analysis revealed that participants showed the highest stress level in 3D=>2D (mean = 4.361, SD = 0.426). No significant difference in stress level was observed between 3D=>3D (mean = 3.75, SD = 0.456), 2D=>2D (mean = 3.889, SD = 0.427) and 2D=>3D (mean = 3.944, SD = 0.426).

- *Emotion:* No significant differences between the dual-display settings were found on emotion, $F_{(3,45)} = 0.504$, $p = 0.31$.

B. Results of radar chart-based usability evaluation

The performance of human-computer interaction negatively correlated with all these indicators, except emotion. Hence, the smaller of the indicator value, the higher rank the information visualization tool gets. Table 1 shows the rank of the dual display settings across the six indicators. Fig. 4 shows the radar chart based on the reciprocal of ranks. The larger the area is covered by the radar chart the better performance is achieved. The radar chart shows that the 3D=>3D display setting achieved the best performance by evaluating from the efficiency of exploration and interpretation based on the six indicators. However, the radar chart shows that more attention was put on the AOIs of the 3D=>3D display setting than the AOIs of 2D=>3D settings. The results may be caused by the longer time required for users to memorize information presented on 3D display.

TABLE I. THE RANKS OF THE FOUR DUAL DISPLAY SETTINGS

Interfaces	FF	FD	FT	W	S	E
2D=>2D	2	1	2	2	1	1
3D=>2D	2	1	2	3	2	1
3D=>3D	1	1	2	1	1	1
2D=>3D	3	1	1	2	1	1

Notes: FF: frequency of fixation; FD: fixation mean duration; FT: fixation time on an AOI; W: workload; S: stress; and E: emotion.

V. CONCLUSION

This study proposes a novel radar-chart-based approach to objectively evaluate usability of the hybrid 2D-3D information visualization tool from two aspects, namely the efficiency of exploration and interpretation. In this study, the efficiency of exploration and interpretation are represented by six indicators, including the frequency of fixations, fixation time on an AOI, fixation duration, workload, stress, and emotion, which were extracted from eye movements and EEG data. The adoption of radar chart and statistical analysis enables the visualization of usability evaluation results from several aspects and reduces the complexity in understanding the statistical analysis.

Though the study has made several contributions, it still has some limitations. Specifically, only six indicators are identified in this study. In the future study, more parameters, such as the length of scan path and saccade velocity can be added to achieve a comprehensive usability evaluation. The other limitation to our study stems from the experiment design. The experiment recruited students as subjects instead of ATCOs. Considering that the experimental tasks are just simulated based on ATC operations, no professional skills and knowledge are required in the experimental tasks, recruiting the student subjects should be fine to generate some meaningful pilot results. In the future, ATCOs should be recruited, and real air traffic control tasks should be designed to test the usability of the hybrid 2D-3D radar display settings.

VI. ACKNOWLEDGMENT

This research is supported by the National Research Foundation, Singapore, under its International Research Centers in Singapore Funding Initiative. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not reflect the views of National Research Foundation, Singapore.

REFERENCES

[1] S. Y. Tan, C. H. Chen, S. W. Lye, and F. Li, “Task Measures for Air Traffic Display Operations,” in *International Conference on Intelligent Human Systems Integration*, 2020, pp. 183–189.

[2] F. Trapsilawati, C. D. Wickens, X. Qu, and C.-H. Chen, “Benefits of imperfect conflict resolution advisory aids for future air traffic control,” *Hum. Factors*, vol. 58, no. 7, pp. 1007–1019, 2016.

[3] F. Trapsilawati, X. Qu, C. D. Wickens, and C.-H. Chen, “Human factors assessment of conflict resolution aid reliability and time pressure in future air traffic control,” *Ergonomics*, vol. 58, no. 6, pp. 897–908, 2015.

[4] Y. Liu *et al.*, “Human factors evaluation of ATC operational procedures in relation to use of 3D display,” in *International Conference on Applied Human Factors and Ergonomics*, 2019, pp. 715–726.

[5] D. K. Hannesson, K. Wolfe, and M. E. Corcoran, “Effects of Kindling on Spatial Memory,” in *Kindling 6*, Springer, 2005, pp. 273–283.

[6] N. R. Council, *The future of air traffic control: Human operators and automation*. National Academies Press, 1998.

[7] M. Tory, A. E. Kirkpatrick, M. S. Atkins, and T. Moller, “Visualization task performance with 2D, 3D, and combination displays,” *IEEE Trans. Vis. Comput. Graph.*, vol. 12, no. 1, pp. 2–13, 2005.

[8] H. S. Smallman, M. S. John, H. M. Oonk, and M. B. Cowen, “Information availability in 2D and 3D displays,” *IEEE Comput. Graph. Appl.*, vol. 21, no. 5, pp. 51–57, 2001.

[9] M. Tavanti and M. Lind, “2D vs 3D, implications on spatial memory,” in *IEEE Symposium on Information Visualization, 2001. INFOVIS 2001.*, 2001, pp. 139–145.

[10] M. St. John, M. B. Cowen, H. S. Smallman, and H. M. Oonk, “The use of 2D and 3D displays for shape-understanding versus relative-position tasks,” *Hum. Factors*, vol. 43, no. 1, pp. 79–98, 2001.

[11] S. Rozzi, P. Amaldi, W. Wong, and B. Field, “Operational potential for 3D displays in air traffic control,” in *Proceedings of the 14th European conference on Cognitive ergonomics: invent! explore!*, 2007, pp. 179–183.

[12] M. Teplan, “Fundamentals of EEG measurement,” *Meas. Sci. Rev.*, vol. 2, no. 2, pp. 1–11, 2002.

[13] Y. Liu *et al.*, “Human Factors Assessment in

VR-based Firefighting Training in Maritime: A Pilot Study," in *2020 International Conference on Cyberworlds (CW)*, 2020, pp. 157–163.
[14] C. Berka *et al.*, "EEG correlates of task engagement and mental workload in vigilance, learning, and memory tasks," *Aviat. Space. Environ. Med.*, vol. 78, no. 5, pp. B231–B244, 2007.
[15] W. L. Lim, O. Sourina, Y. Liu, and L. Wang, "EEG-based mental workload recognition related to multitasking," in *2015 10th International Conference on Information, Communications and Signal Processing (ICICS)*, 2015, pp. 1–4.
[16] J. Cui *et al.*, "A Compact and Interpretable Convolutional Neural Network for Cross-Subject Driver Drowsiness Detection from Single-Channel EEG," *Methods*, 2021.
[17] E. M. Reingold, "Eye tracking research and technology: Towards objective measurement of data quality," *Vis. cogn.*, vol. 22, no. 3–4, pp. 635–652, 2014.
[18] D. Topolšek, I. Areh, and T. Cvahte, "Examination of driver detection of roadside traffic signs and advertisements using eye tracking," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 43, pp. 212–224, 2016, doi: 10.1016/j.trf.2016.10.002.
[19] E. Koletsis, C. P. J. M. van Elzakker, M.-J. Kraak, W. Cartwright, C. Arrowsmith, and K. Field, "An investigation into challenges experienced when route planning, navigating and wayfinding," *Int. J. Cartogr.*, vol. 3, no. 1, pp. 4–18, 2017.
[20] S. Ishimaru, S. S. Bukhari, C. Heisel, J. Kuhn, and A. Dengel, "Towards an intelligent textbook: eye gaze based attention extraction on materials for learning and instruction in physics," in *Proceedings of the 2016 ACM International Joint Conference on Pervasive and Ubiquitous Computing: Adjunct*, 2016, pp. 1041–1045.
[21] O. Li, F., Chang, D., Liu, Y., Cui, J., Feng, S., Huang, N., & Sourina, "Evaluation of Humanoid Robot Design Based on Global Eye-Tracking Metrics," in *Transdisciplinary Engineering for Complex Socio-technical Systems–Real-life Applications: Proceedings of the 27th ISTE International Conference on Transdisciplinary Engineering, July 1–July 10, 2020*, 2020, vol. 12, p. 241.
[22] F. Li, C. H. Lee, C. H. Chen, and L. P. Khoo, "Hybrid data-driven vigilance model in traffic control center using eye-tracking data and context data," *Adv. Eng. Informatics*, vol. 42, no. June, p. 100940, 2019, doi: 10.1016/j.aei.2019.100940.
[23] K. Holmqvist, M. Nyström, R. Andersson, R. Dewhurst, H. Jarodzka, and J. Van de Weijer, *Eye tracking: A comprehensive guide to methods and measures*. OUP Oxford, 2011.
[24] F. Li, C. H. Chen, G. Xu, and L. P. Khoo, "Hierarchical Eye-Tracking Data Analytics for Human Fatigue Detection at a Traffic Control Center," *IEEE Trans. Human-Machine Syst.*, vol. 50, no. 5, pp. 465–474, 2020, doi: 10.1109/THMS.2020.3016088.
[25] F. Li, C. H. Chen, G. Xu, L. P. Khoo, and Y. Liu, "Proactive mental fatigue detection of traffic control operators using bagged trees and gaze-bin analysis," *Adv. Eng. Informatics*, vol. 42, no. January, p. 100987, 2019, doi: 10.1016/j.aei.2019.100987.
[26] R. N. Meghanathan, C. van Leeuwen, and A. R. Nikolaev, "Fixation duration surpasses pupil size as a measure of memory load in free viewing," *Front. Hum. Neurosci.*, vol. 8, p. 1063, 2015.
[27] X. Hou *et al.*, "CogniMeter: EEG-based brain states monitoring," in *Transactions on Computational Science XXVIII*, Springer, 2016, pp. 108–126.