Exploring the effects of background colour and gender on cognitive performance of visual attention: a multimodal approach using fNIRS and eye-tracking

Lina Xu[*†‡], Bojing Hou[†], Xingkai Wang[†‡], Zhongyue Zhang[†] and Luwen Yu[†‡]

†*The Hong Kong University of Science and Technology (GuangZhou), Guangzhou, China*
‡*The Hong Kong University of Science and Technology, Hong Kong, China*
**Emails: lxu582@connect.hkust-gz.edu.cn; lxu582@connect.ust.hk*

The interplay between background colour and individual characteristics such as gender significantly influences cognitive performance in visual attention tasks. While colour's role in cognition has been studied, the impact of low-saturation colours and their gender-specific interactions remains underexplored. This study examined the effects of nine background colours—seven low-saturation hues (red, orange, yellow, green, cyan, blue, purple), standard grey, and standard white—on visual attention among 54 participants (27 males, 27 females) in a dark psychophysical laboratory. A multimodal approach combined cognitive performance data (accuracy and search time), functional near-infrared spectroscopy (fNIRS) data (activation of brain regions associated with visual attention), and eye-tracking measures (fixation and pupil metrics). Results revealed that males exhibited higher accuracy and faster search times on cyan and yellow backgrounds, whereas females demonstrated greater neural activation on orange and cyan backgrounds. Eye-tracking data indicated longer fixation durations for females on orange backgrounds and higher cognitive load for males on blue backgrounds. Correlation analysis revealed contrasting cognitive strategies, females showed a positive correlation between search time and accuracy, while males exhibited a negative correlation. These findings underscore the nuanced role of gender-specific responses to background colour in shaping visual cognition. Insights gained have applications in human-computer interaction, educational tools, and tailored interventions for cognitive impairments.

Received 02 December 2024; revised 20 January 2025; accepted 21 January 2025
Published online: 16 March 2025

Introduction

In today's rapidly evolving information technology landscape, cognitive abilities are increasingly significant in learning, work, and daily life [1-3]. Data from the World Health Organization (WHO) indicate that 1 billion people—approximately 15% of the global population—are affected by varying degrees of mental or cognitive disorders [4-6]. These challenges not only impact individual quality of life and work efficiency but may also have profound effects on socio-economic development [7-9]. Enhancing individual cognitive performance becomes particularly crucial. Among cognitive functions, Visual Attention (VA) is vital for information selection and processing, forming the foundation for learning, decision-making, and problem-solving [10-13]. Understanding the factors influencing visual attention performance is therefore crucial for enhancing cognitive efficiency and developing effective intervention strategies.

Colour, as a significant characteristic of visual stimuli, profoundly influence individuals' allocation and concentration of attention [14-16]. Existing studies have demonstrated that colour affects emotions, psychological states, and cognitive processes, enabling improved attention concentration and interaction with information systems [15, 17-20]. Despite this, previous research has focused on highly saturated or three primary colours, with limited analysis of low-saturation backgrounds [21-23]. Furthermore, evidence suggests that males and females may exhibit distinct attention allocation strategies [24-27], yet the interaction between gender and background colour in visual cognition remains underexplored. Additionally, previous studies have typically used a single method (e.g. behavioural data or self-report data) to assess cognitive performance [28-30], which ignores the relationship between brain activities performance and cognitive responses. On the other hand, the functional near-infrared spectroscopy (fNIRS) monitors cerebral blood flow changes in real time, which shows the ability to understanding the activation of brain regions associated with VA [31-33]. Meanwhile, Eye-tracking technology provides quantitative analysis of visual attention allocation and decision-making processes [34-35].

Therefore, this study investigates how nine background colours, including seven low-saturation hues (red, orange, yellow, green, cyan, blue, purple) and two achromatic colours (grey and white), influence visual attention. By combining cognitive performance data (accuracy and search time), fNIRS-based brain activation data, and eye-tracking metrics (fixation duration and pupil diameter), this research addresses the following objectives:

1. Examine cognitive performance differences in visual attention performance across genders under varying background colours.
2. Explore patterns of brain activation associated with visual attention tasks using fNIRS data, with an emphasis on gender-specific differences.
3. Correlating accuracy and search time integrates cognitive performance data to uncover potential cognitive strategies.

Method

Colour conditions

To investigate the influence of background colours on visual attention, this study employed nine background colours within the CIELAB colour space. These included seven low-saturation hues (red, orange, yellow, green, cyan, blue, purple) and two achromatic colours (grey and white). By focusing on low-saturation colours, this study aims to explore nuanced behavioural and physiological patterns across genders in visual attention tasks.

All colours, except white, were standardised to maintain consistent luminance, ensuring that luminance contrast effects were controlled. Grey characters were displayed against the white background, while white characters were presented on all other coloured backgrounds. Lightness (L^*) and chromaticity (a^*, b^*) values were measured in a display by using a JETI specbos 1211 UV-2 spectroradiometer. As shown in Table 1, ΔL^* ranged from -0.73 to 1.18, while ΔE spanned 0.91 to 11.02.

Although certain ΔE values, such as green (ΔE = 11.02) and cyan (ΔE = 10.55), indicated noticeable numerical differences, these variations were perceptually negligible, allowing them to be treated as equivalent colours. This controlled setup ensured experimental reliability, providing a foundation for analysing the interactions between background colour and gender-specific visual attention responses.

Colour	Target			Real			ΔL^*	ΔE
	L^*	a^*	b^*	L^*	a^*	b^*		
Grey	50	0	0	50.46	-0.78	0.12	0.46	0.91
Red	50	22.00	11.00	51.10	29.31	13.61	1.10	7.84
Orange	50	13.00	22.00	51.18	17.75	26.71	1.18	6.79
Yellow	50	1.00	25.00	50.67	2.28	29.75	0.67	4.96
Green	50	-20.00	13.00	49.50	-31.01	12.99	-0.50	11.02
Cyan	50	-13.25	-7.00	49.27	-23.66	-8.56	-0.73	10.55
Blue	50	-2.15	-24.00	49.50	-9.73	-25.34	-0.50	7.71
Purple	50	20.00	-13.00	50.96	23.83	-11.54	0.96	4.21
White	90	0	0	89.70	-0.77	-0.83	-0.30	1.17

ΔL^*: Lightness difference between target and real

ΔE: Colour difference between target and real

Table 1: CIE chromaticity coordinates of the colours used in the experiment.

Experimental procedures

The experimental design aimed to simulate realistic visual attention cognitive tasks while maintaining controlled conditions for reliable data collection provided by the PsyToolkit platform. Participants performed a visual search task, a widely recognised paradigm for studying attention, where the goal was to identify a target—a positive "T"—among 20 distractor icons (see Figure 1a). This task, frequently encountered in daily life, was chosen to align with the study's objective of examining behavioural and physiological responses under varying colour conditions [36].

Each trial began with a 2000ms display of the stimulus, followed by a 500ms grey screen to reset participants' visual attention. There were 15 trials per background colour, with each block lasting 30 seconds, interspersed with 30-second rest periods displayed in standard grey (L^* = 50). The experimental conditions and tasks were presented in randomised order to minimise bias and ensure balanced data collection across all colour conditions.

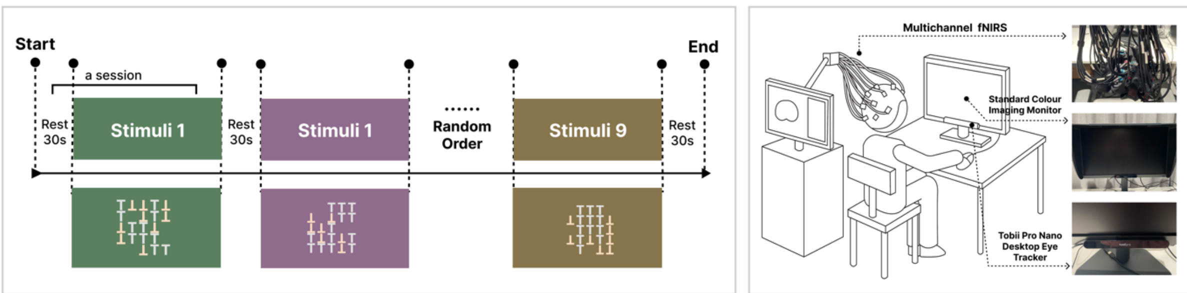

Figure 1 (a): Experimental task procedures **Figure 1 (b): Schematic of the experiment**

Figure 1: Experimental procedural and setting.

All experiments were conducted in a standardised dark, silent psychophysical laboratory to eliminate external distractions and maintain consistency in lighting. As shown in Figure 1b, Participants were seated 60-65 cm from a 27-inch Dell UP2720Q professional monitor (3840 × 2160 resolution), ensuring a controlled visual angle of less than 0.5 degrees. The setup included simultaneous recordings of brain activity using a 106-channel functional near-infrared spectroscopy (fNIRS) system (KY-A, Wuhan YIRUIDE Group) and eye-tracking data with a Tobii Pro Nano desktop eye tracker, providing synchronised multimodal data for comprehensive analysis.

Participants

Fifty-eight participants took part in this experiment. After screening for data quality, 54 participants (27 males and 27 females) were included, as shown in Table 2, the age range was 17-36 years (M = 23.89, SD = 3.71). All participants were ensured to be without cognitive impairment and completed the Ishihara Colour Vision Test, at the end of the experiment, participants were appropriately compensated.

This study was approved by the institutional ethics committee (ref: HKUST(GZ)-HSP-2024-0062). Before participation, all individuals were informed of the study's purpose, procedures, and potential risks. Written informed consent was obtained from each participant, ensuring voluntary participation and the right to withdraw at any stage without consequences.

Demographic variable	Item	Number	Percentage
Gender	Male	27	50%
	Female	27	50%
Age	Average age	23.89	---
	Age range	17-36	---
Education	College/BA	16	30%
	Master	26	48%
	PhD	12	22%

Table 2: Demographic data of participants.

Results

Data preprocessing was done prior to the analysis, and the average accuracy and average search time were calculated for the 15 trials in each condition. Raw data preprocessing for the multichannel fNIRS instrument was performed in MATLAB 2014b, Homer2, NIRS_KIT [36-37]. The data were first corrected for motion artefacts, filtered and processed, and converted to optical density, then the optical density signal was converted to changes in blood oxygen concentration using Beer-Lambert's law [38-40], and finally oxygenated haemoglobin (HbO) data were extracted from VA-related brain regions during the task based on the labelled task start and end times. Eye-tracking data were then computed from the raw data to obtain fixation as well as pupil metrics. Descriptive statistics were performed to summarise the cognitive performance (search time + accuracy), VA-related brain region activation, and eye-tracking metrics for male and female participants in the different colour conditions. Mixed ANOVA analyses were conducted with gender (male and female) as a between-subjects factor and nine background colours as a within-subjects factor. to assess the effect of background colour on cognitive performance, brain region activation, and eye-tracking metrics across gender. In addition, correlation analyses were conducted to explore the relationship between the cognitive performance data to further elucidate underlying cognitive mechanisms. All statistical analyses were performed using SPSS v27.0 software, and the significance level was set at $p < 0.05$.

Cognitive performance data

Accuracy performance

Figure 2a shows the mean accuracy across gender in different background colours, with male participants generally having higher mean accuracy than female participants in all conditions (Male: M = 0.816, Female: M = 0.723). Males performed best on the cyan background (M = 0.869), yellow

(M = 0.841) and red background (M = 0.839), and performed relatively poorly in terms of accuracy on the white background (M = 0.763). In contrast, female participants performed best against a white background (M = 0.758), followed by similar performance against orange, red, green, and grey (M > 0.738). Table 3 presents the interaction effects of gender, colour, and gender and colour, which showed gender had a significant effect on participants' accuracy rates (F (1, 52) = 5.705, p = 0.02*, η_P^2 = 0.096). In particular, the greatest differences in performance between males and females were found in the cyan background (MD = 0.178, SE = 0.057, p = 0.003*) and yellow background (MD = 0.160, SE = 0.058, p = 0.008*). However, the interaction of background colour, colour and gender had no significant effect on accuracy.

Search time performance

In terms of mean search time, as shown in Figure 2b, the overall mean search time for male participants was slightly faster than that of female participants (Male: M = 1.820, Female: M = 1.856), and males had the fastest search time against the white (M = 1.648) and grey background (M = 1.692). Females show faster search times on purple (M = 1.797) and grey (M = 1.821). Table 3 also shows the results of the ANOVA, where the gender variable did not have a statistically significant effect on participants' search times. Background colour, on the other hand, had a significant effect on search times (F (8, 52) = 2.317, p = 0.019*, η_P^2 = 0.043), and both males and females had slower search times on orange than on the other colours.

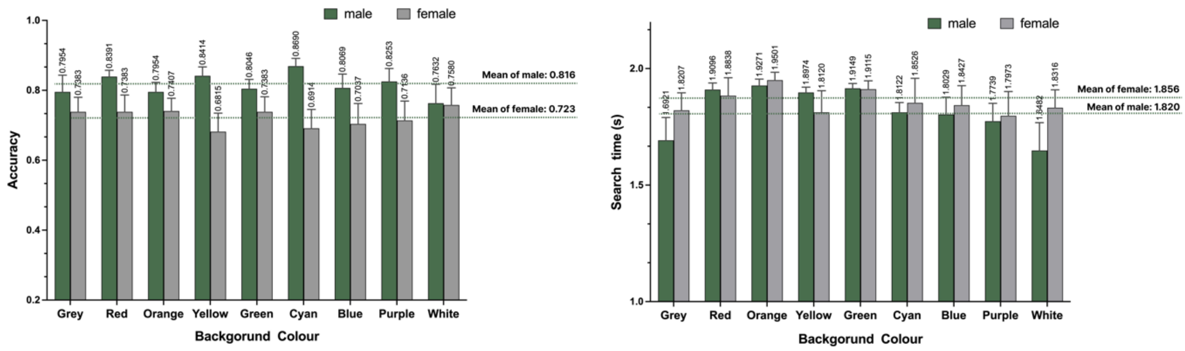

Figure 2 (a): Accuracy of gender in different colours

Figure 2 (b): Search time of gender in different colours

Figure 2: Accuracy and search time of gender in different colours.

Source	Variable	SS	DF	MS	F	p
Accuracy	Gender	1.087	1	1.087	5.705*	**0.020***
	Colour	0.047	8	0.006	0.178	0.977
	Gender × Colour	0.326	8	0.041	1.241	0.288
Search time	Gender	0.157	1	0.157	0.385	0.538
	Colour	2.095	8	0.262	2.317*	**0.019***
	Gender × Colour	0.685	8	0.086	0.758	0.640

Table 3: Effects of gender and colour and gender × colour on accuracy and search time.

Correlation analysis of accuracy and search time

To better understand the relationship between the cognitive performance data, this study correlated correctness and search time using Pearson's correlation coefficient, which helped to provide insight into the cognitive strategies of participants of different genders.

Figure 3 shows the correlation between search time and accuracy for participants of different genders under different background colours, with females showed a significant positive correlation between search time and accuracy under almost all background colours, especially under cyan (r = 0.67, p < 0.001*) and grey (r = 0.62, p < 0.001*) backgrounds. Meanwhile, there was a significant negative correlation between search time and accuracy for males, especially in the yellow background (r = -0.48, p < 0.01*), verifying that the shorter the search time, the higher the accuracy for male participants.

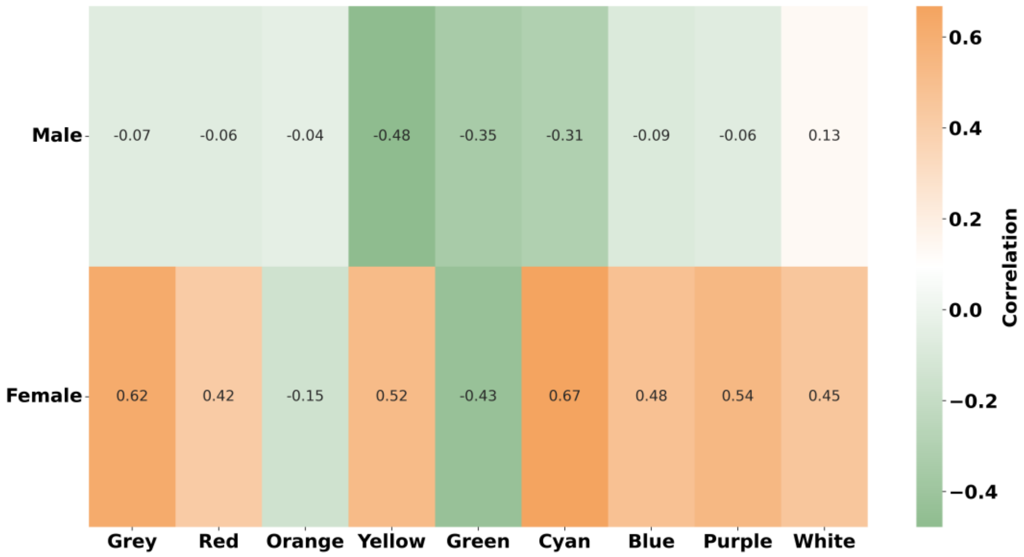

Figure 3: Correlation between accuracy and search time.

Brain activities data (fNIRS)

The left occipital cortex (OC-L)

As shown in Figure 4a, data from fNIRS showed that in the region of the left occipital cortex (OC-L/R) of the hindbrain, which is involved in basic visual perception and recognition when processing visual information, activation in female participants was higher than that in male participants in all background conditions (Male: M = 0.011 , Female: M = 0.039), and particularly in the orange (M = 0.043) and red backgrounds (M = 0.042) with higher activation. And as can be seen in Table 4 gender had a significant effect on the activation of this region in participants (F (1, 52) = 11.737, p = 0.001*, η_P^2 = 0.184). It was also in the condition of orange background (p = 0.001*) that the difference in activation between male and female was the greatest (see Table 5).

The left frontal eye field (FEF-L)

As shown in Figure 4b, in the left prefrontal eye field (FEF-L), which involves visual attention, oculomotor control, and orientation of visual information, activation in female participants was similarly significantly higher than that in male participants in all background conditions (Male: M = -0.005 , Female: M = 0.011), and activation was higher in the blue colour (M = 0.015) and cyan colour (M = 0.014). The main effect of gender can likewise be seen to be significant in Table 4 (F (1, 52) = 6.091, p = 0.017*, η_P^2 = 0.105). Female participants showed the greatest difference in activation levels from males on the orange background (p = 0.019*) and cyan background (p = 0.005*) (see Table 5). Thus, in Figure 5, an activation map of male and female brain regions against an orange background was made, and a clear difference in activation can be seen in these two VA-related brain regions.

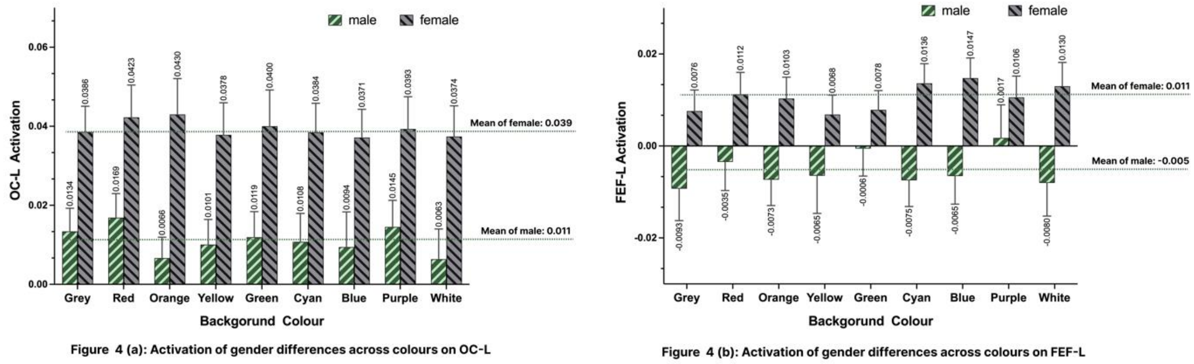

Figure 4: Activation of gender differences across colours on OC-L and FEF-L.

Source (ROI)	Variable	SS	DF	MS	F	p
OC - L	Gender	0.097	1	0.097	11.737*	**0.001***
	Colour	0.002	8	<0.001	0.42	0.909
	Gender × Colour	0.001	8	<0.001	0.273	0.974
FEF - L	Gender	0.031	1	0.031	6.091*	**0.017***
	Colour	0.002	8	<0.001	0.698	0.693
	Gender × Colour	0.003	8	<0.001	0.952	0.473

Table 4: Effects of gender and colour and gender × colour on OC-L and FEF-L.

Variable	Colour	MD	SE	p	95% CI
OC - L	Orange	0.036	0.01	**0.001***	0.015-0.057
	Yellow	0.028	0.01	**0.010***	0.007-0.048
	Green	0.028	0.011	**0.016***	0.006-0.051
	Cyan	0.028	0.01	**0.010***	0.007-0.048
FEF - L	Orange	0.018	0.007	**0.019***	0.003-0.032
	Cyan	0.021	0.007	**0.005***	0.007-0.035

Table 5: Pairwise comparisons of gender differences across colours on OC-L and FEF-L (female vs male).

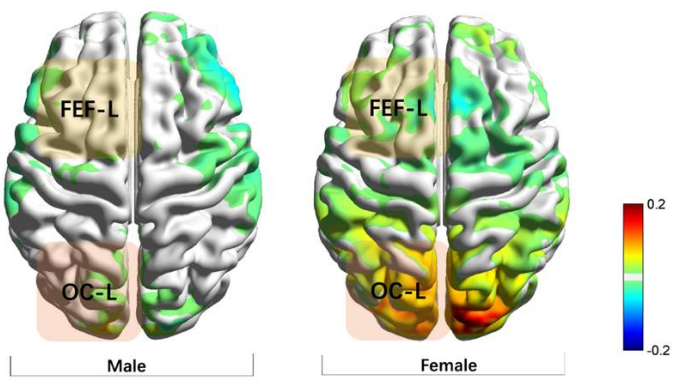

Figure 5: Activation of gender differences across orange.

The eye-tracking data

Fixation duration

Female participants had significantly longer fixation duration on all backgrounds than male participants (Male: M = 267.695, Female: M = 307.255), as shown in Figure 6a. Female subjects had longer fixation duration on white, orange, and cyan colours (M > 312). Gender had a significant effect on mean fixation duration (F (1, 52) = 7.427, p = 0.009, η_P^2 = 0.125). In particular, there was a large difference in the time taken by males and females to process information on orange and cyan (p < 0.025*), as shown in Tables 6 and 7.

Pupil diameter

Furthermore, as shown in Figure 6b, male participants had larger pupil diameters than female participants on all backgrounds (Male: M = 3.605, Female: M = 3.332), especially on grey (M = 3.796) and green (M = 3.747). Moreover, the effects of gender (F (8, 52) = 4.363, p = 0.042, η_P^2 = 0.077) as well as colour (F (8, 52) = 109.568, p < 0.001, η_P^2 = 0.678) on pupil diameter were similarly significant, with male participants on cyan backgrounds (p = 0.02*) showing higher cognitive load than female participants and attention.

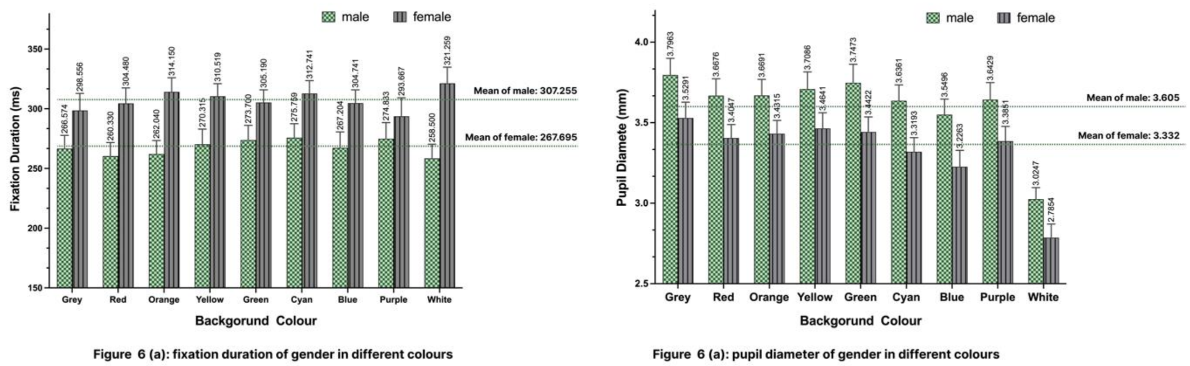

Figure 6: Fixation duration and pupil diameter of gender in different colours.

Source (ROI)	Variable	SS	DF	MS	F	p
Average Fixation Duration	Gender	190143.558	1	190143.558	7.427*	**0.009***
Pupil Diameter	Colour	21.864	8	2.733	109.568*	**<0.001***
	Gender	9.036	1	9.036	4.363*	**0.042***

Table 6: Effects of gender and colour on fixation duration and pupil diameter.

Variable	Colour	MD	SE	p	95% CI
Fixation Duration	Orange	52.111	16.441	**0.003***	19.119-85.103
	Cyan	36.981	16.017	**0.025***	4.841-69.122
Pupil Diameter	Cyan	-0.317	0.132	**0.020***	-0.582--0.052
	Blue	-0.323	0.141	**0.026***	-0.606--0.041

Table 7: Pairwise comparisons of gender differences across colours on fixation duration and pupil diameter (female vs male).

Discussion and conclusions

This study highlights the significant influence of gender on cognitive performance in visual attention tasks, revealing distinct cognitive performance, brain activation patterns, and cognitive strategies under different background colours. By employing a multimodal approach that integrates cognitive performance data, functional near-infrared spectroscopy (fNIRS), and eye-tracking metrics, the research provides a comprehensive analysis of how background colours interact with gender-specific cognitive processes. This method allows for an objective examination of the impact of visual stimuli on cognitive load, combining behavioural and physiological data to uncover underlying mechanisms.

The findings reveal that males generally exhibit higher accuracy and faster search times, particularly on cyan, yellow, and red backgrounds, suggesting an advantage in processing visual stimuli and efficiently locating targets. Females, in contrast, demonstrated slightly slower search times and lower accuracy, which may reflect the engagement of greater cognitive resources during task performance [41-43]. These cognitive performance differences were further supported by fNIRS data, which showed higher brain activation levels in females, particularly in regions associated with visual attention, such as the left occipital cortex (OC-L) and frontal eye field (FEF-L). Eye-tracking metrics complemented these findings by indicating longer fixation durations for females, consistent with a more detailed and comprehensive cognitive strategy. Males, on the other hand, displayed a negative correlation between search time and accuracy, reflecting a preference for quicker decision-making [44-47].

Despite these contributions, the study has limitations. The sample size, while balanced by gender, is relatively small and drawn from a specific demographic, limiting the generalisability of the findings. Additionally, while the experimental design-controlled luminance and chromaticity differences, individual perceptual variations were not directly measured. Future research could address these limitations by including larger, more diverse populations and incorporating subjective evaluations of colour perception to complement the objective metrics.

The results have practical implications across several domains. For human-computer interaction, the findings provide insights into optimising interface design through gender-sensitive use of background colours. In educational tools, tailoring background colours could enhance focus and reduce cognitive load, especially for tasks requiring sustained attention. Furthermore, the study's methodology demonstrates the potential of multimodal data integration for investigating cognitive performance, offering a robust framework for future research.

Overall, this study advances the understanding of how background colour and gender interact to shape cognitive performance, contributing to the broader fields of cognitive science, interaction design, and educational psychology. By emphasising the importance of gender-specific responses, it opens new avenues for developing targeted applications that improve cognitive efficiency and user experience.

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