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Title Page

Effects of Color Scheme and Visual Fatigue on Visual Search Performance and Perceptions under Vibration Conditions

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Abstract

Visual search represents one of the most encountered human–computer interaction tasks. However, the effect of visual fatigue on visual search, especially in conditions involving vibrations, remains largely known. The objective of this study was to assess the effects of color scheme and visual fatigue on visual search performance and perceptions in different vibration conditions. We conducted an experiment in which 24 participants performed four visual-search tasks involving different numbers of targets. Each search task was based on a three-way (2 × 3 × 24) within-subjects design that comprised two visual-fatigue statuses (high and low visual fatigue), three vibration conditions (static, fore-and-aft, and lateral vibration), and 24 color schemes for the visual search interfaces. The outcomes were visual search performance (i.e., task completion time and accuracy), perceptions (i.e., mental workload, perceived task difficulty, and discomfort), and user preference. Visual fatigue and color schemes significantly affected task completion time in all four visual search tasks ($p < 0.05$) but only partially influenced accuracy in certain tasks. The vibration environment did not affect task completion time and accuracy in any task. Visual fatigue and vibration significantly affected mental workload and perceived task difficulty ($p < 0.001$). Discomfort was affected only by visual fatigue ($p = 0.001$) but not affected by vibration. White-on-black and yellow-on-black were the preferred color schemes in the high visual fatigue and low visual fatigue conditions, respectively ($p < 0.05$). The findings have practical implications for the design of human–computer interfaces in conditions involving vibrations and visual fatigue. (250 words)

Keywords: Visual search; visual fatigue; color scheme; vibration

1. Introduction

Visual search is one of the most commonly encountered human–computer interaction tasks in daily life and work [1]. During visual search, humans use their eyes to collect visual information and locate specific targets [2]. Although visual search on visual display terminals (VDTs) has gained popularity in ergonomics studies in past decades [e.g., 3, 4, 5], visual fatigue and discomfort caused by visual search activities have always been considered critical ergonomic problems in the interface design of visual displays [5]. The problems can be even worse when visual search is performed in conditions involving vibrations [6, 7], poorly designed interfaces [8, 9], or prolonged visual fatigue status [10, 11]. However, little is known about the visual search performance in these situations.

In fact, a growing number of cockpits on transportation vehicles (e.g., watercrafts, aircrafts, spacecrafts, and automobiles and flight decks) have equipped with varied VDTs in the past two decades, meaning that visual search activities (e.g., target detection on radar system) could be increasingly performed under vibration conditions [8]. For example, pilots must find enemy targets quickly on complex radar interfaces in VDTs during flight tasks. People usually need to spend more efforts (both physically and mentally) to keep task performance in vibration conditions compared with that in static environment [12]. Thus, visual search could become more challenging under vibration conditions due to their potentially negative influence. However, the negative influence of vibration on visual search has rarely been examined.

Interface design characteristics and users' psychophysiological status (e.g., fatigue status) may also influence visual search performance in vibration conditions. For example, color, as one of the most effective features among interface design characteristics, holds the key to increasing the effectiveness of information and graphical displays. Previous studies have focused on examining color scheme to achieve the optimal information display [13]. In addition, visual fatigue is a typical psychophysiological status that often occurs in visual search tasks, especially in a prolonged period. It can bring a series of negative physiological, psychological, or emotional responses during visual search tasks and further result in performance decrement of human visual system [14-16]. However, few studies have explored visual search by jointly considering interface design characteristics (e.g., color scheme) and users' psychophysiological status (e.g., whether users are in fatigued), especially under vibration conditions.

Therefore, the objective of this study was to evaluate the effects of visual fatigue, color schemes, and vibration conditions on visual search performance (e.g., task completion time and accuracy) and perceptions (e.g., mental workload, perceived difficulty, discomfort, and user preference) in visual search tasks and to examine how these three factors interact with one another. We based our study scenario on visual search activities that are commonly performed on VDTs in the cockpits of ships, flight decks, and aircraft. Our findings are expected to assist designers and ergonomists in designing improved VDT interfaces for cockpits in modern vehicles.

The rest of this paper is organized as follows: Section 2 presents related work on visual search in vibration conditions and provide a foundation for our research by building on prior knowledge. Section 3 describes the details of methods, including the experimental design, participants, apparatus and materials, experimental tasks, procedures, and data analysis. Section 4 presents the results from the experiment. Section 5 discusses the main findings regarding vibration, color scheme, and visual fatigue, and brings about study limitations, followed by the conclusion drawn from the study.

2. Related Work

2.1 Visual search and vibration

Visual search activities (e.g., target detection on radar systems) are being increasingly performed in conditions involving vibrations, given that a growing number of cockpits on vehicles (e.g., automobiles, ships, and flight decks) are equipped with various VDTs [8]. Previous studies reported that vibration frequency and amplitude could adversely affect response time and accuracy, and cause visual fatigue during task performance with computer displays [17-19]. Vibration can also affect user perception and balance ability, leading to poor performance in perception and balance control [17, 20]. It can also increase difficulties in performing cognitive, mental, and physical tasks [6-8, 19, 21, 22] and lead to increased visual fatigue [23]. Overall, people need to expend additional physical and mental effort to perform human–computer interaction tasks under vibration conditions than in a static environment [12, 24]. This means that it is more challenging to perform visual search under vibration conditions than under a static condition. However, how varied vibration conditions exert negative influence on visual search has less been examined and warrant further examination.

2.2 Visual search and color scheme

Among several interface design characteristics (such as the stimulus form [25], size [26], color scheme [27], and shape [28]), the color scheme is key to enhancing target salience and improving visual search performance [29]. In addition, appropriate color selection can increase the effectiveness of information and graphical displays [8, 13, 30]. Many researchers have explored optimal color schemes in various scenarios. For example, primary colors (i.e., red, green, and blue) were shown to be more conspicuous than colors derived from mixing primary colors [31]. The attentional target-selection characteristics of monochrome visual search interfaces have been found to be significantly different from those of polychromatic visual search interfaces [25, 32]. Moreover, it was found that there is a U-shaped relationship between the number of colors and search time [33], and that a combination of colors with strong contrast are preferred in interface design [34]. Color combinations are classified into those with positive and negative polarities, respectively [8, 35]. Positive (negative) polarity refers to cases in which the target and background have colors with lower and higher (higher and lower) luminance values, respectively [8, 35-38]. However, mixed results have been obtained regarding the effects of color polarity. Although some reports state that positive polarity can enhance visual discrimination and perceived comfort [10, 36, 39, 40], other studies recommend the use of negative polarity (e.g., yellow-on-black and white-on-black) as optimal color combinations for presenting information on search interfaces [8]. Additionally, several studies have reported no difference in people's visual performance when using positive and negative polarity displays, respectively [41]. Overall, although extensive research has been performed on the influence of color schemes on visual performance, the results have been mixed, and the possible contribution of color schemes to visual performance in vibration environments has received little attention. In particular, whether the negative influence of vibration on visual performance can be partially mediated by an appropriate color scheme remains unknown.

2.3 Visual search and visual fatigue

Visual fatigue is a typical psychophysiological status that is often experienced in visual search tasks and can lead to negative physiological, psychological, or emotional responses [42] that can further deteriorate the performance of the human visual system [14-16]. For example, Sheedy, Hayes, Engle and Jon [16] found that exposure to persistent visual fatigue may result in headaches and affect work efficiency and safety in VDT tasks. Several researchers have examined the mitigating effects of color schemes on visual fatigue [41, 43, 44]. For example, Xie, Song, Liu, Wang and Yu [43] evaluated the effects of color polarity and luminance contrast on visual fatigue and noted that high luminance contrast and negative polarity (i.e., a white target on a black background) may alleviate visual fatigue. However, despite the extensive research on visual fatigue, the influence of the visual fatigue induced in visual search activities on subsequent visual-search performance remains to be clarified. In addition, only a few researchers have explored the differences between the effects of color schemes in varied visual fatigue conditions, especially under vibration conditions.

3. Methods

3.1 Experimental design

The experiment was based on a three-way (24 × 3 × 2) within-subjects design. The three independent variables were color scheme of the information interface (i.e., 24 color schemes), vibration condition (i.e., static, lateral, and fore-and-aft conditions), and visual fatigue status (i.e., low and high visual fatigue). Color scheme was the configuration of the target and background colors that were used to present target elements on visual search interfaces. Following previous studies and given the widespread applications of color combinations on the legibility of text/target presented on Liquid Crystal Displays (LCDs) [8, 37, 45, 46], we applied the red–green–blue (RGB) color model to define our color schemes with eight colors: three primary colors, i.e., red (RGB: 255, 0, 0), green (RGB: 0, 255, 0), and blue (RGB: 0, 0, 255); three secondary colors mixed with two of the three primary colors, i.e., yellow (green and red, RGB: 255, 255, 0), turquoise (blue and green, RGB: 0, 255, 255), and purple (red and blue, RGB: 255, 0, 255); and two achromatic colors, i.e., black (RGB: 0, 0, 0) and white (RGB: 255, 255, 255). Previously, we noted that black and blue present the lowest luminance, whereas white and yellow present the highest luminance [8]. Thus, for the negative polarity cases, the background colors were black and blue, and the other six colors were used as the target colors. Similarly, for the positive polarity cases, yellow and white were used as the background colors, and the other six colors were used as the target colors [10, 13]. Finally, 24 color schemes were designed (Table 1 and Appendix A). Considering the restrictions pertaining to naval personnel safety and personnel performance stipulated by the North Atlantic Treaty Organization (NATO;[47] and previous vibration studies [6, 8], three vibration conditions were defined (Table 2).

The high visual fatigue condition was induced by requesting the participants to perform visual fatigue-inducing tasks for 1 hour before the formal experimental tasks. The visual fatigue-inducing tasks were similar to the formal experimental tasks in terms of the interface design but differed in terms of the presentation of stimuli (visual fatigue-inducing tasks used letters (i.e., O, P, Q, C, and D) as stimuli) (Figure 1). Additionally, the interface for the visual fatigue-inducing tasks had a yellow background with cyan stimuli, which was noted to cause eyestrain in our pilot test and was thus considered effective for inducing visual fatigue. The stimuli appeared randomly on the interface, with the number of targets being 0, 1, 2, or 3 in each task. One of the five letters was randomly selected as the target and indicated at the top of the interface, and the other four letters were distractors. The participants were asked to search the interface area and identify all of the target letters by clicking on them with a mouse. If no target was identified, the participants were instructed to press the "Enter" key on the keyboard. The introduction of visual fatigue was verified by the critical fusion frequency (CFF) and eye-complaint questionnaire (ECQ) [48], which have been widely used to assess visual fatigue in different visual-display work environments [49]. The CFF was measured using a flicker fusion device (H133331, Zhongruixiang Tech, China). The ECQ was administered through 10 items, each rated on a 7-point scale (from 0, denoting "not at all," to 6, denoting "very much"). An increase in visual fatigue was indicated by a decreased CFF and an increased ECQ score [49]. For the low visual fatigue condition, the participants were requested to rest for 1 hour before the experiment.

Table 1. The 24 color schemes designed by image polarity, background color, target color, and contrast ratio.

Image	Background	Target	Color scheme	Codes	Contrast
Negative	Black	Yellow	1) Yellow on black	Y/BK	208.5
		White	2) White on black	W/BK	226.2
		Green	3) Green on black	G/BK	161.9
		Red	4) Red on black	R/BK	41.3
		Turquoise	5) Turquoise on	T/BK	169.7
		Purple	6) Purple on black	P/BK	64.7
	Blue	Yellow	7) Yellow on blue	Y/BL	10.1
		White	8) White on blue	W/BL	11.0
		Green	9) Green on blue	G/BL	7.6
		Red	10) Red on blue	R/BL	1.2
		Turquoise	11) Turquoise on	T/BL	8.0
		Purple	12) Purple on blue	P/BL	2.5
Positive	Yellow	Black	13) Black on yellow	BK/Y	-1.0
		Blue	14) Blue on yellow	BL/Y	-0.9
		Green	15) Green on yellow	G/Y	-0.2
		Red	16) Red on yellow	R/Y	-0.8
		Turquoise	17) Turquoise on	T/Y	-0.2
		Purple	18) Purple on yellow	P/Y	-0.7
	White	Black	19) Black on white	BK/W	-1.0
		Blue	20) Blue on white	BL/W	-0.9
		Green	21) Green on white	G/W	-0.3
		Red	22) Red on white	R/W	-0.8
		Turquoise	23) Turquoise on	T/W	-0.3
		Purple	24) Purple on white	P/W	-0.7

Table 2. Parameters for the three vibration conditions.

Vibration	Static condition		Fore-and-aft vibration condition		Lateral vibration condition	
Degree of freedom	Amplitude	Period	Amplitude	Period	Amplitude	Period
Sway	± 0 mm	0 s	± 0 mm	0 s	± 0 mm	0 s
Heave	± 0 mm	0 s	± 0 mm	0 s	± 0 mm	0 s
Surge	± 0 mm	0 s	± 0 mm	0 s	± 0 mm	0 s
Pitch	± 0°	0 s	± 10°	4 s	± 0 °	0 s
Yaw	± 0°	0 s	± 0 °	0 s	± 10°	4 s
Roll	± 0°	0 s	± 0°	0 s	± 0°	0 s

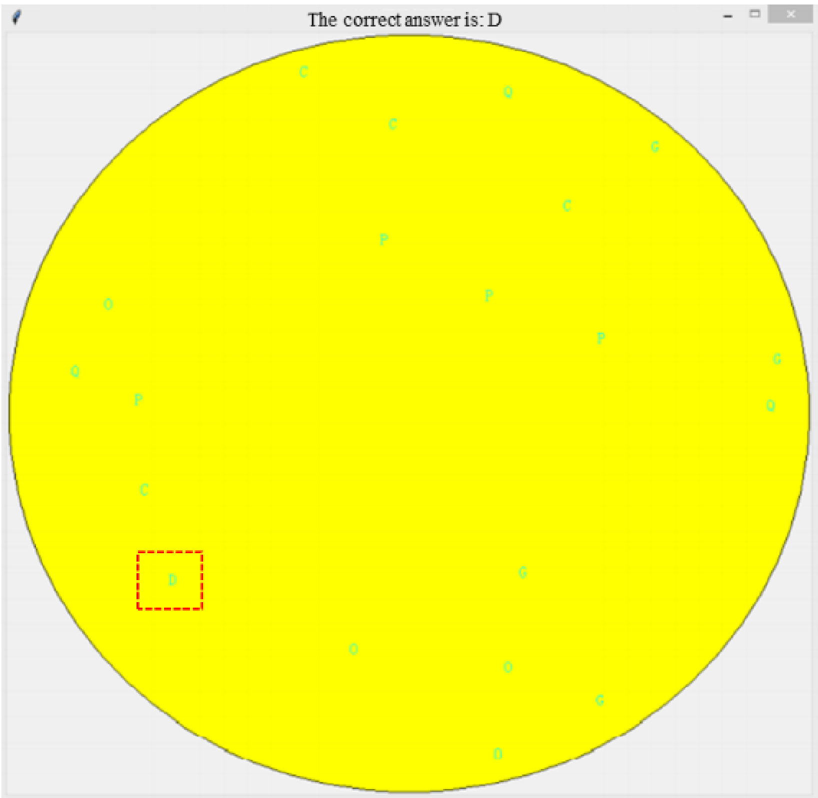

Figure 1. An example of visual search interfaces for visual fatigue-inducing tasks (with the letter D as the target as marked in the red rectangle).

The dependent variables were user performance (task completion time and accuracy), user perceptions (mental workload, perceived difficulty, and discomfort), and user preferences. The task completion time (in seconds) was the time participants needed to complete a visual search task. The accuracy (%) was defined as the percentage of correct responses. A correct response was recorded if the participants correctly identified the target(s). The mental workload was measured by the NASA Task Load Index (NASA-TLX) on a 100-point scale [50], which has been widely used as a subjective workload assessment in various human–computer interaction scenarios [7, 51-53]. The perceived task difficulty was defined as the extent to which the participants perceived the visual search task as difficult, measured on a 5-point Likert scale (from 1, denoting "very easy," to 5, denoting "very difficult") [6]. The discomfort referred to the level of discomfort participants generally perceived, measured by a Likert discomfort scale rated from 0 (no discomfort) to 10 (extremely strong discomfort) [8, 54]. The user preference was evaluated by asking participants to indicate the extent to which they preferred the use of certain color schemes for visual search tasks.

3.2 Participants

Twenty-four university students (12 men and 12 women) aged 21.9 ± 2.1 years were recruited using a convenience sampling method. Based on our preliminary study [52], this sample was considered to be sufficient for detecting a medium effect size of 0.3 with 80% statistical power and a significance level of 5%. All of the participants self-reported that they were proficient in reading and writing Chinese, did not experience motion sickness or seasickness, and had normal, or correct-to-normal vision and no color vision deficiency. Their vision acuity was verified by vision tests with the Standard Logarithmic Visual Acuity chart that was widely used in clinical settings in China [55]. The results showed that the participants on average had mean vision acuity of 4.30, (SD = 0.3). Informed consent was obtained before the experiment. The institutional review board of the university approved this study.

3.3 Apparatus and materials

A six-degrees-of-freedom Stewart Platform (Model: PT-6-75L-1000S, Foshan Yishili Tech) was used to simulate vibration conditions (Figure 2). The Stewart Platform could display six-degree motions up to the following ranges: heave (y-axis) ± 25 cm, sway (x-axis) ± 25 cm, surge (z-axis) ± 25 cm, pitch ± 16°, roll ± 16°, and yaw ± 25°. An all-in-one Dell computer (screen size: 23 in; pixel resolution: 1600 × 900) was installed on the platform to present visual search tasks. Following the literature [56], the screen was positioned at a 90° angle to the desk surface. MATLAB was used to develop a computer application to present experimental stimuli and record the participants' responses. A wireless mouse (M186, Logitech) was used as the input device in the visual search tasks.

3.4 Experimental tasks

An experimental interface was designed by simplifying and simulating a ship radar interface to present experimental stimuli, similar to the plan-position indicator (PPI) pattern of a classic radar display [57, 58]. The PPI located the radar at the center of the display, and the circular path indicated the maximum detection distance from the center (Figure 2). The experimental stimuli comprised three types of targets and six types of distractors, as presented in Figure 3 with icon size information. Four experimental tasks were designed based on the number of target icons presented on the display interface, i.e., no-target, single-target, dual-target, and triple-target tasks.

In all tasks, the total number of target and distractor icons was 28, set based on the opinions of two marine human-factors experts and on the design of practical radar detection charts. In order to mimic the real situations, we programed the computer application to randomly place the stimuli icons of targets and distractors on the radar interface mock-up (see Figure 2). The stimuli icons were kept in the same size across all the experimental tasks. The icon size was designed according to the Handbook for Human Engineering Design by the US Department of Defense [59], and was determined as 30 arcmin (corresponding to a displayed size of 5.24 mm on the experimental interface), which could be an optimal stimulus size at a viewing distance of 510–635 mm for VDTs.

When the participants detected a target, they were required to press the "Space" key on the keyboard to activate a responsive interface (Figure 3), which asked them to select the target type and location (i.e., above-zone or below-zone). If the participants saw no target, they were required to select the "No target" button. The next visual search task was presented after the previous task had been completed.

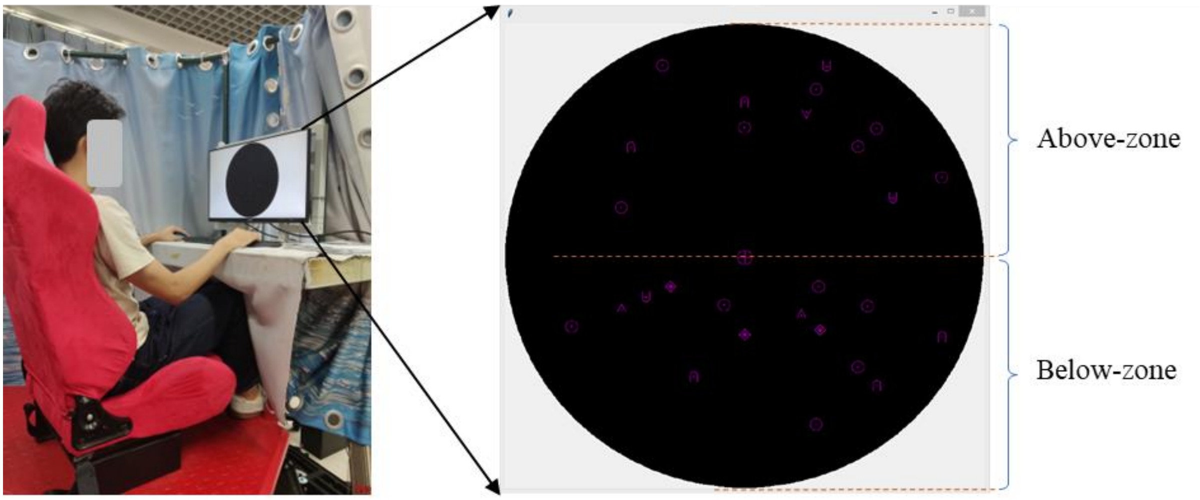

Figure 2. The six-degrees-of-freedom platform utilized for the simulation of vibration conditions (left), and an example of the radar interface mock-up, with the purple target on a black background (right).

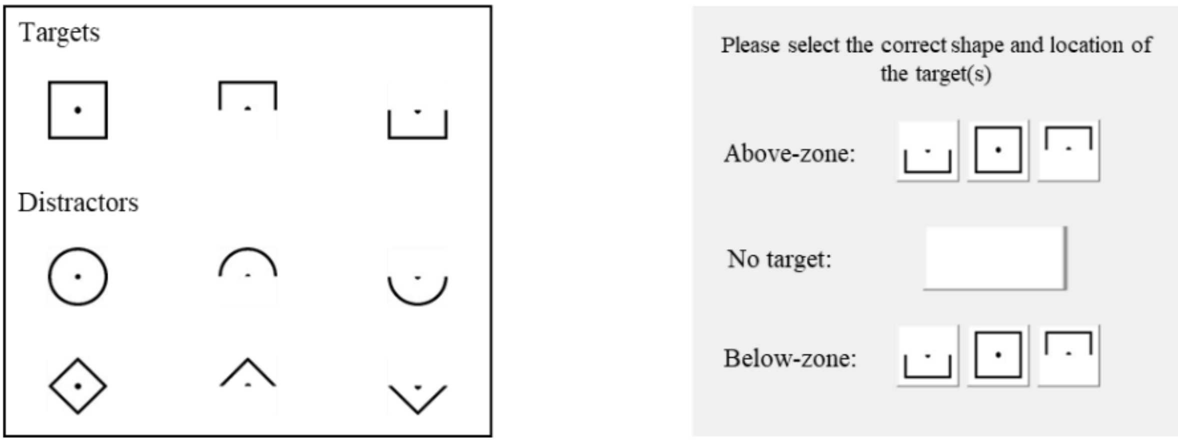

Figure 3. Illustration of experimental stimuli (left) and responsive interface (right).

3.5 Procedures

All of the participants provided written informed consent upon their arrival at our university laboratory. The participants were guided to complete 10 minutes of practice tasks to familiarize themselves with the laboratory-based experiment. For the high visual fatigue condition, the participants were instructed to perform visual-fatigue-inducing tasks for 1 hour before the experiment. For the low visual fatigue condition, the participants were first requested to rest for 1 hour in the laboratory. They were allowed to enjoy less visually or mentally demanding activities, such as remaining in a silent and calm state or listening to music. Next, the main test was initiated. The participants were required to complete 288 trials (24 color schemes × 4 task types × 3 repetitions) as rapidly and accurately as possible under each of six combinations of fatigue status and vibration conditions (1,728 trials in total). To reduce order effects, the testing sequence of fatigue status and vibration condition was counterbalanced using a Latin Square design [60], while task types and color schemes were randomized within each of the six combinations of fatigue status and vibration conditions (1,728 trials in total). The CFF and ECQ were measured before and after the visual-fatigue-inducing tasks for the high visual fatigue condition, and before and after the main tests for both the high and low visual fatigue conditions. Moreover, the participants were requested to complete questionnaires assessing subjective mental workload, discomfort, and task difficulty after they completed all tasks under each combination of fatigue status and vibration condition (i.e., 288 trials). The user preference was evaluated after the completion of all of the tasks in each visual fatigue condition. The main test lasted for approximately half hour for each vibration condition, after which the participants took a 5-min break. To ensure research fidelity, each participant performed the experiment on different days (with a gap of at least one day) for the high and low visual fatigue conditions.

3.6 Data analysis

Data normality for the visual search performance and perception measures was verified by the Shapiro–Wilk test. The paired sample t-test was performed to compare the significance of the differences in the CFF and ECQ values. Repeated-measures analyses of variance were performed to assess the effects of visual fatigue, vibration, and color scheme on the dependent variables. Mauchly's test was conducted to evaluate sphericity. If the sphere hypothesis was violated, Greenhouse–Geisser estimates of sphericity were used for data correction. Post-test comparisons were performed with the Bonferroni adjustment method. User preference for the different color schemes was analyzed using a chi-square (χ^2) test. Statistical analyses were conducted using IBM SPSS 22 (Chicago, Illinois, USA).

4. Results

The following sections describe the results of the effects of vibration, color scheme, and visual fatigue on task completion time, accuracy, and subjective perceptions. No significant interaction effect was observed between visual fatigue, color scheme, and vibration conditions on the completion time for any of the tasks (all p values > 0.05), or on the accuracy for any of the tasks (all p values > 0.05).

4.1 Vibration

Table 3 presents the main effects of the vibration condition on the completion time and accuracy for the visual search tasks. The vibration condition did not significantly affect the task completion time for the no-target task, $F(1.287, 29.600) = 0.152$, $p = 0.762$; single-target task, $F(2, 46) = 0.038$, $p = 0.963$; dual-target task, $F(1.554, 35.749) = 0.263$, $p = 0.714$; or triple-target task, $F(2, 46) = 0.717$, $p = 0.494$. The vibration condition did not significantly affect the accuracy in the no-target task, $F(2, 46) = 2.701$, $p = 0.078$; single-target task, $F(2, 46) = 0.717$, $p = 0.494$; dual-target task, $F(2,46) = 1.486$, $p = 0.237$; or triple-target task, $F(1.481, 34.052) = 1.097$, $p = 0.329$.

Table 3. Main effects of vibration conditions on task completion time (s) and accuracy (%), stratified by visual search tasks.

Vibration	No-target task	Single-target task	Dual-target task	Triple-target task
Task completion time (s)				
Static	4.4 (0.37)	2.4 (0.18)	4.0 (0.23)	5.5 (0.27)
Lateral	4.6 (0.23)	2.4 (0.16)	3.9 (0.24)	5.3 (0.28)
Fore-and-aft	4.5 (0.26)	2.4 (0.15)	4.0 (0.25)	5.4 (0.28)
Accuracy (%)				
Static	85.0 (0.50)	26.5 (0.20)	17.4 (0.16)	11.9 (0.12)
Lateral	92.9 (0.37)	28.3 (0.21)	18.8 (0.12)	13.1 (0.10)
Fore-and-aft	96.4 (0.21)	29.5 (0.13)	20.4 (0.13)	14.1 (0.12)

4.2 Color scheme

Table 4 presents the main effects of the color scheme on the completion time and accuracy for the visual search tasks. The color scheme significantly affected the completion time of all of the tasks, i.e., no-target task, $F(8.812, 202.667) = 3.502$, $p = 0.001$; single-target task, $F(23, 529) = 1.871$, $p = 0.009$; dual-target task, $F(9.857, 226.709) = 2.358$, $p = 0.012$; and triple-target task, $F(8.919, 205.136) = 4.737$, $p < 0.001$. Figure 4 presents the task completion time for different color schemes.

Table 4. Main effects of color scheme on task completion time (s) and accuracy (%), stratified by visual search tasks.

Color scheme	No-target task	Single-target task	Dual-target task	Triple-target task
Task completion time (s)				
P/BK	4.7 (0.29)	2.3 (0.14)	3.9 (0.25)	5.8 (0.35)
R/BK	4.5 (0.26)	2.4 (0.18)	4.1 (0.31)	5.4 (0.29)
G/BK	4.3 (0.24)	2.2 (0.15)	4.2 (0.29)	5.7 (0.38)
T/BK	4.5 (0.25)	2.6 (0.21)	4.0 (0.22)	5.6 (0.30)
Y/BK	4.4 (0.31)	2.6 (0.15)	3.9 (0.22)	5.5 (0.31)
W/BK	4.5 (0.28)	2.6 (0.17)	4.1 (0.23)	6.0 (0.28)
P/BL	5.4 (0.28)	2.7 (0.17)	4.6 (0.27)	6.6 (0.48)
R/BL	4.6 (0.26)	2.3 (0.16)	3.8 (0.19)	5.2 (0.30)
G/BL	4.1 (0.24)	2.5 (0.16)	4.4 (0.39)	5.4 (0.31)
T/BL	4.7 (0.24)	2.3 (0.17)	4.1 (0.34)	5.6 (0.28)
Y/BL	4.5 (0.22)	2.5 (0.21)	3.7 (0.22)	5.3 (0.24)
W/BL	4.4 (0.27)	2.5 (0.19)	3.8 (0.25)	5.0 (0.22)
P/Y	4.4 (0.24)	2.2 (0.16)	3.6 (0.23)	4.7 (0.26)
R/Y	4.4 (0.23)	2.2 (0.17)	3.9 (0.25)	4.9 (0.26)
G/Y	4.3 (0.22)	2.3 (0.20)	3.8 (0.29)	5.4 (0.38)
T/Y	4.8 (0.26)	2.8 (0.18)	4.3 (0.24)	6.1 (0.41)
BK/Y	4.3 (0.22)	2.4 (0.17)	4.0 (0.29)	5.0 (0.29)
BL/Y	4.5 (0.28)	2.3 (0.17)	3.7 (0.27)	5.0 (0.33)
P/W	4.4 (0.27)	2.2 (0.15)	3.6 (0.25)	4.9 (0.33)
R/W	4.2 (0.19)	2.4 (0.19)	3.7 (0.16)	5.0 (0.28)
G/W	4.4 (0.24)	2.4 (0.20)	3.7 (0.27)	5.0 (0.33)
T/W	4.6 (0.26)	2.6 (0.18)	4.3 (0.26)	5.7 (0.31)

BK/W	4.3 (0.21)	2.4 (0.18)	3.9 (0.28)	5.0 (0.23)
BL/W	4.3 (0.28)	2.2 (0.17)	3.8 (0.28)	5.4 (0.31)
Accuracy (%)				
P/BK	93.1 (0.26)	27.1 (0.36)	21.5 (0.37)	16.0 (0.39)
R/BK	90.3 (0.28)	34.0 (0.35)	19.4 (0.50)	12.5 (0.27)
G/BK	93.1 (0.22)	22.9 (0.39)	22.2 (0.36)	11.8 (0.26)
T/BK	89.6 (0.28)	28.5 (0.42)	16.7 (0.28)	16.7 (0.40)
Y/BK	91.0 (0.28)	25.7 (0.41)	18.1 (0.37)	11.8 (0.23)
W/BK	93.1 (0.24)	26.4 (0.36)	19.4 (0.30)	11.8 (0.35)
P/BL	93.7 (0.24)	31.3 (0.42)	15.3 (0.33)	13.9 (0.24)
R/BL	91.7 (0.27)	31.9 (0.32)	18.8 (0.35)	9.70 (0.22)
G/BL	92.4 (0.30)	32.6 (0.35)	16.7 (0.32)	13.2 (0.25)
T/BL	92.4 (0.25)	31.2 (0.29)	20.1 (0.35)	16.7 (0.32)
Y/BL	92.4 (0.27)	32.6 (0.38)	21.5 (0.38)	16.0 (0.31)
W/BL	91.0 (0.28)	27.1 (0.37)	17.4 (0.29)	10.4 (0.28)
P/Y	89.6 (0.30)	27.1 (0.44)	16.7 (0.25)	14.6 (0.34)
R/Y	90.3 (0.28)	30.6 (0.51)	22.2 (0.34)	9.70 (0.24)
G/Y	91.0 (0.27)	21.5 (0.32)	16.7 (0.48)	9.70 (0.22)
T/Y	92.4 (0.25)	27.8 (0.34)	19.4 (0.33)	13.2 (0.32)
BK/Y	91.7 (0.27)	25.0 (0.33)	23.6 (0.30)	10.4 (0.22)
BL/Y	91.7 (0.22)	25.7 (0.35)	13.9 (0.28)	17.4 (0.31)
P/W	91.7 (0.28)	25.7 (0.36)	21.5 (0.39)	10.4 (0.24)
R/W	88.2 (0.32)	31.3 (0.42)	19.4 (0.30)	11.1 (0.22)
G/W	92.4 (0.27)	22.9 (0.33)	22.2 (0.42)	13.9 (0.30)
T/W	90.3 (0.28)	27.8 (0.40)	18.1 (0.30)	14.6 (0.34)
BK/W	91.0 (0.28)	30.6 (0.37)	17.4 (0.31)	13.9 (0.26)
BL/W	91.0 (0.32)	27.1 (0.47)	14.6 (0.25)	13.9 (0.30)

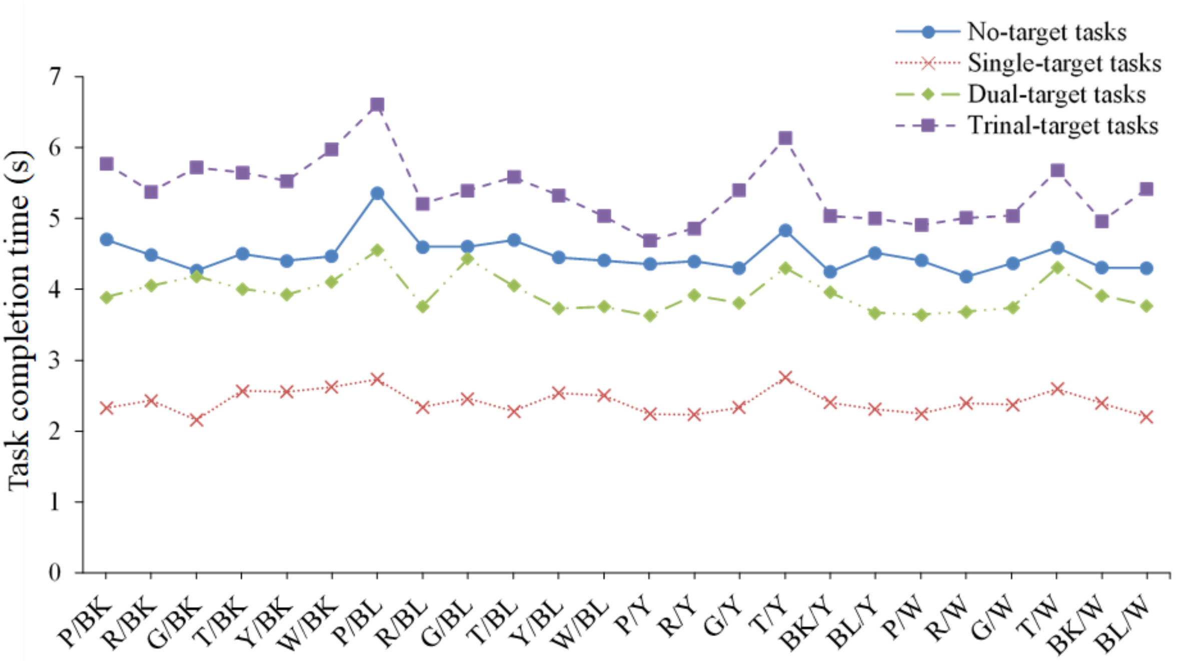

Figure 4. Task completion time (s) by color scheme and visual search task types

The color scheme did not significantly affect the accuracy in the no-target task, $F(23, 529)$

= 1.106, p = 0.333; single-target task, F(23, 529) = 0.830, p = 0.695; dual-target task, F(10.303, 236.959) = 0.610, p = 0.810; or triple-target task, F(11.420, 262.663) = 0.701, p = 0.743. Figure 5 presents the accuracy for different color schemes.

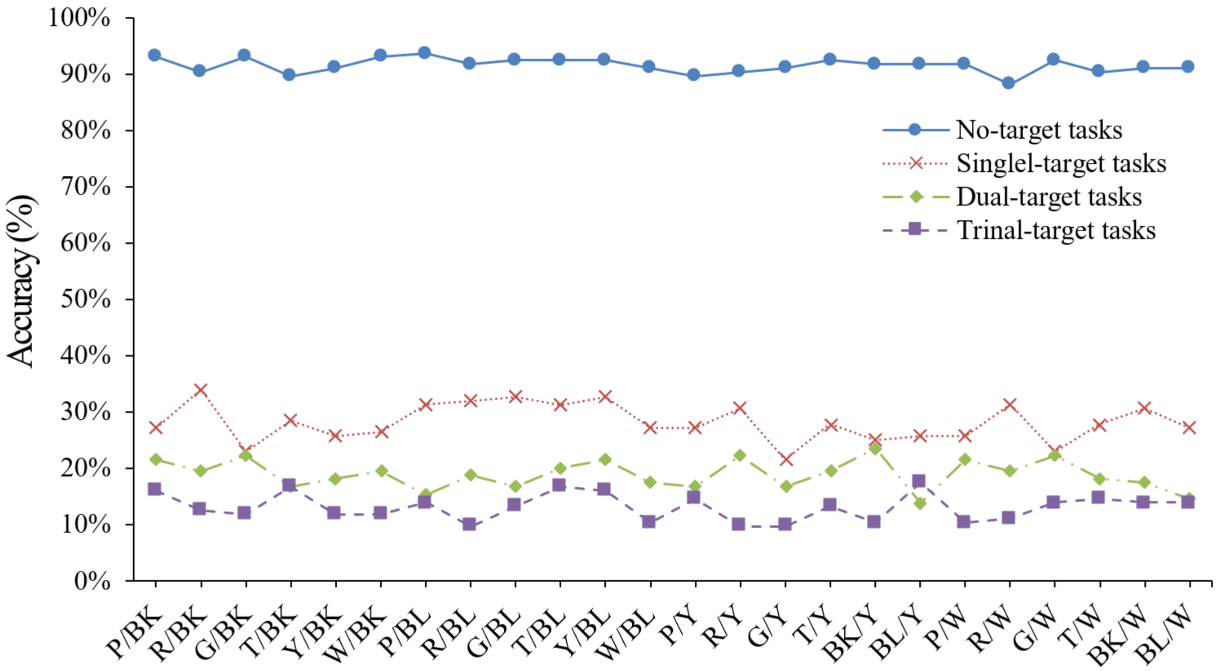

Figure 5. Accuracy (%) by color scheme and visual search task types

4.3 Visual fatigue

For the high visual fatigue condition, the ECQ score increased (from 14.9 to 33.7; t = -6.133, p < 0.001) after the participants had performed the visual fatigue-inducing tasks, whereas the CFF showed a non-significant decrease from 16.3 to 16.1 (t = 0.525, p = 0.605). The difference in the CFF before and after the main test was 0.8 Hz and 0.2 Hz for high and low visual fatigue conditions, respectively. These findings indicated that visual fatigue was successfully induced in the high visual fatigue condition.
Table 5 presents the main effects of visual fatigue on the completion time and accuracy for the visual search tasks. Visual fatigue significantly affected the completion time for all of the tasks, i.e., no-target task, F(1, 23) =22.660, p < 0.001); single-target task, F(1, 23) = 25.076, p < 0.001; dual-target task, F(1, 23) = 34.369, p < 0.001; and triple-target task, F(1, 23) = 30.364, p < 0.001). Figure 6 presents the task completion time for different visual fatigue conditions.

Table 5. Main effects of visual fatigue on task completion time (s) and accuracy (%), stratified by visual search tasks.

Visual fatigue	No-target task	Single-target task	Dual-target task	Triple-target task
Task completion time (s), mean (SD)				
High	5.1 (0.31)	2.8 (0.18)	4.6 (0.28)	6.2 (0.34)
Low	3.9 (0.18)	2.1 (0.11)	3.4 (0.16)	4.6 (0.21)
Accuracy (%), mean (SD)				
High	90.2 (0.33)	27.3 (0.14)	19.3 (0.31)	11.6 (0.10)
Low	92.7 (0.26)	28.9 (0.16)	18.4 (0.59)	14.5 (0.10)

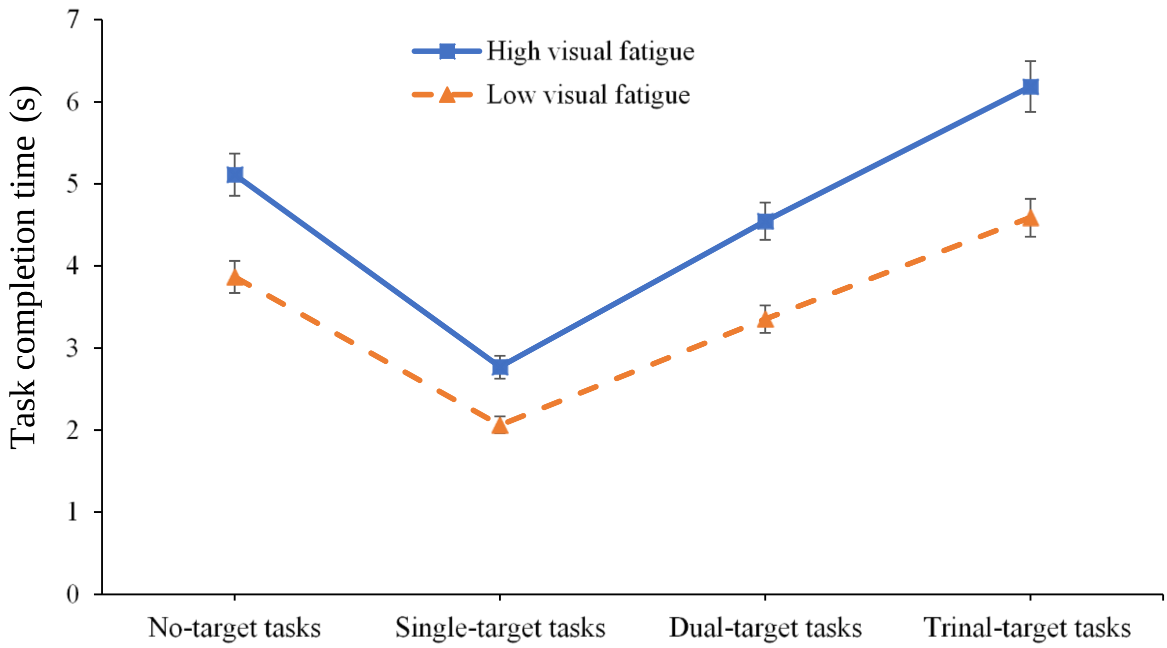

Figure 6. Task completion time (s) by visual fatigue and visual search task types

Visual fatigue had a significant effect only in the triple-target task, $F(1, 23) = 5.081$, $p = 0.034$. Non-significant effects were noted in the no-target task, $F(1, 23) = 0.581$, $p = 0.454$; single-target task, $F(1, 23) = 0.689$, $p = 0.415$; and dual-target task, $F(1, 23) = 0.305$, $p = 0.586$. Figure 7 presents the task completion accuracy for different visual fatigue levels.

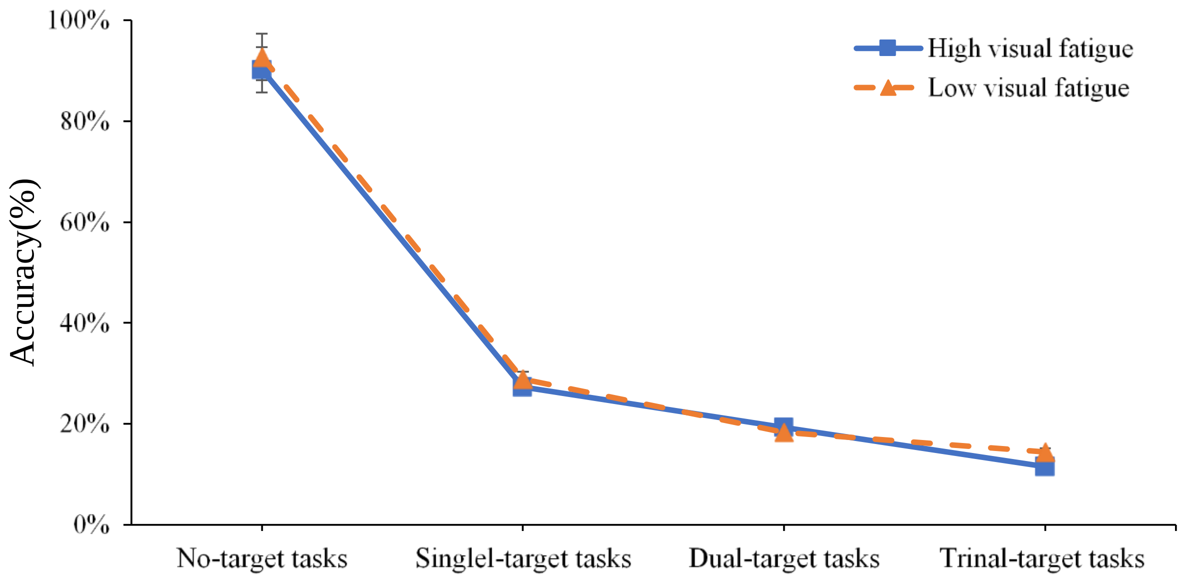

Figure 7. Accuracy (%) by visual fatigue and visual search task types

4.4 Subjective perceptions

As shown in Table 6, visual fatigue significantly affected mental workload, $F(1, 23) = 21.253$, $p < 0.001$; perceived task difficulty, $F(1, 23) = 18.133$, $p < 0.001$; and discomfort, $F(1, 23) = 8.412$, $p = 0.001$. The vibration condition significantly affected the mental workload, $F(1.550, 35.660) = 14.704$, $p < 0.001$ and perceived task difficulty, $F(2, 46) = 8.518$, $p = 0.001$, but not the discomfort level, $F(2, 46) = 1.895$, $p = 0.182$. No significant interaction effect was observed between visual fatigue and vibration on the perception measures.

Table 6. Mean values (SDs) of mental workload, perceived task difficulty, and discomfort stratified by levels of visual fatigue and vibration condition.

	Mental workload	Perceived task difficulty	Discomfort
Visual fatigue			
High	47.7 (3.20)	2.8 (0.19)	-0.6 (0.50)
Low	38.1 (2.90)	2.1 (0.16)	-1.3 (0.30)
Vibration conditions			
Static	38.6 (2.50)	2.1 (0.19)	-0.4 (0.30)
Lateral	44.2 (3.10)	2.6 (0.16)	-1.2 (0.30)
Fore-and-aft	45.9 (3.30)	2.7 (0.20)	-1.2 (0.40)

Table 7 presents the distribution of user preference for the background and target colors in both visual fatigue conditions. The participants preferred black (frequency: 38.89%) or white (frequency: 36.11%) backgrounds ($\chi^2 = 16.971$, $p < 0.001$). There was no dominant color preference for the target ($\chi^2 = 6.667$, $p = 0.051$), with turquoise being the most frequently selected (19.44%). The participants preferred the white-on-black color scheme ($\chi^2 = 60.000$, $p < 0.001$; frequency: 13.89%). In the low visual fatigue condition, the participants preferred black backgrounds (frequency: 63.89%; $\chi^2 = 62.556$, $p < 0.001$) and yellow targets (frequency: 29.17%; $\chi^2 = 36.889$, $p < 0.001$), and the preferred color scheme was yellow-on-black (frequency: 25.00%; $\chi^2 = 198.667$, $p < 0.001$).

Table 7. User preference percentage on background color and target color for both low and high visual fatigue conditions.

	Low visual fatigue	High visual fatigue
Background color		
Black	38.9%	64.0%
Blue	15.3%	6.9%
Yellow	9.7%	6.9%
White	36.1%	22.2%
Target color		
Purple	2.8%	5.5%
Red	4.2%	13.9%
Turquoise	19.4%	12.5%
Green	15.3%	18.1%
Yellow	12.4%	29.2%
White	15.3%	18.1%
Black	15.3%	0
Blue	15.3%	2.7%

5. Discussion

This study aimed to investigate the effects of visual fatigue and color schemes on visual search performance in vibration conditions. In general, vibration did not significantly affect task performance but it significantly affected mental workload and perceived task difficulty. The color scheme significantly affected task completion time and accuracy. Visual fatigue significantly influenced visual search performance (i.e., task completion time and accuracy) and perceptions (i.e., mental workload, perceived task difficulty, and discomfort).

5.1 Effects of vibration

Significant effects of vibration on task performance were not observed in the visual search tasks. This finding is consistent with those of several other studies [8, 18]. Wang, Tao, Liu, Zhou and Qu [8] examined visual search performance in three vibration conditions (static, low, and high) and found that vibration had no significant influence on task completion time and accuracy. Goode, Lenné and Salmon [18] noted that vibration did not affect the performance of information processing operations (e.g., reading tasks). Tables 3 and 4 highlight that visual search performance under static, lateral, and for-and-aft vibrations was similar in all of the tasks. The movability and balance of an individual are affected by motion caused by vibration, which can deteriorate manipulation capability [61], e.g., in human–computer interactions (e.g., dragging and pointing) with different input devices [6, 7]. Overall, it appears that the effect of vibration may be more prominent in activities requiring physical control than in those involving information processing (e.g., visual search), and this aspect must be further explored. Another potential reason for the absence of significant effects is that the exposure to vibration conditions in our study was low, which might have resulted in underestimation of the influence of vibration on cognitive performance. Nevertheless, our findings illustrate that vibration has a significant influence on mental workload and perceived task difficulty, similar to reported results [7]. The participants likely exerted additional mental resources to maintain their task performance. We speculate that if individuals are exposed to vibration for a longer time than in this study (e.g., by spending several hours performing visual search activities, as in actual scenarios) [62], the adverse effects of vibration may become more obvious, and this aspect must be explored in future studies.

5.2 Effects of color scheme

The color scheme significantly affected completion time and accuracy for all of the visual search tasks. The color schemes with the lowest task completion time for the no-target, one-target, dual-target, and triple-target tasks were green-on-blue (mean = 4.061 s), green-on-black (mean = 2.155 s), purple-on-yellow (mean = 3.631 s), and purple-on-yellow (mean = 4.688 s), respectively. The superior performance of purple-on-yellow and green-on-black was previously reported [8], as these two color schemes corresponded to the shortest completion time. The color schemes with the highest accuracy for the no-target, one-target, dual-target, and triple-target tasks were purple-on-blue (mean = 93.7%), red-on-black (mean = 34.0%), black-on-yellow (mean = 23.6%), and blue-on-yellow (mean = 17.4%). The color scheme with the shortest task-completion time and highest accuracy corresponded to a negative polarity case for both no-target and one-target tasks, consistent with reported results [8, 13, 63]. This finding suggests that the use of negative polarity (a light target color on a dark background) can help to decrease response time. In contrast, in the case of dual-target and triple-target tasks, the color schemes with the shortest task-completion times and highest accuracies corresponded to positive polarity. Thus, as the number of targets increases, a dark target color on a light background color results in high performance. Studies have reported mixed results regarding visual search performance in negative and positive polarity cases [8]. Our findings imply that the influence of color polarity on visual search performance depends on the number of targets. However, the reason for this warrant further exploration. In terms of subjective preference, black was preferred as the background color, and light colors (e.g., turquoise and yellow) were preferred as target colors. These findings indicate that the participants preferred the use of negative polarity for visual search, as it enhanced user experience. Therefore, future studies could consider user preference in the selection of color schemes.

5.3 Effects of visual fatigue

We found that visual fatigue significantly affected task completion time, consistent reported results [14-16, 42]. When individuals suffered from visual fatigue (in the high visual fatigue condition), their task completion times were 32.3%, 34.1%, 35.7%, and 34.8% higher in the no-target, one-target, dual-target, and triple-target tasks, respectively, compared with those in the low visual fatigue condition. Furthermore, although the high visual fatigue condition led to decreased accuracy in the triple-target tasks, the accuracy rates were comparable between the two visual fatigue conditions for other tasks. The influence of visual fatigue likely intensified as the task difficulty increased. Moreover, our findings highlight that visual fatigue negatively affected the participants' perceptions, e.g., mental workload, perceived task difficulty, and discomfort. This finding is consistent with those of other studies, which reported negative physiological, psychological, and emotional responses in the high visual fatigue condition [42]. Thus, it is likely that individuals select their preferred color schemes (e.g., white-on-black) to mitigate the adverse effects of visual fatigue in visual search tasks. However, we failed to detect interaction effects between color schemes and visual fatigue. Future studies could be aimed at identifying the color scheme that is most likely to be effective in mitigating the adverse effect of visual fatigue.

5.4 Implications

Our findings have several practical implications. First, the non-significant effects of vibration on visual search performance shows that the interface design developed for the static situation could have been used, with appropriate adjustments, for similar vibration scenarios in our study. Second, color scheme plays an important role in visual search tasks, and thus an appropriate color scheme must be used in human–computer interfaces, e.g., a negative-polarity scheme (i.e., a light target color on a dark background) can be used for non-target and one-target search tasks, and a positive-polarity scheme (i.e., a dark target color on a light background) can be used for visual search tasks with more than two targets. Third, visual fatigue significantly affects visual search performance and subjective perceptions. Therefore, appropriate duty switches must be scheduled to mitigate visual fatigue before the conduction of visual search tasks. Fourth, the participants' subjective preferences regarding color schemes show that they attempted to use color schemes to mitigate the potential influences of visual fatigue, e.g., they preferred white-on-black in the high visual fatigue condition and yellow-on-black in the low visual fatigue condition. Overall, our results show that designers must consider subjective preferences for and objective performances of color schemes in the design of human–computer interfaces to alleviate the negative influence of visual fatigue.

5.5 Limitations and future work

This study had several limitations that must be addressed in future work. First, we induced visual fatigue by requesting the participants to perform a visual search task for 1 hour before the main tasks and evaluated the changes in ECQ and CFF. Although the ECQ significantly increased after the visual fatigue-inducing tasks, the changes in CFF (from 0.8 Hz to 0.2 Hz) were insignificant. Future studies could explore alternative methods for inducing visual fatigue and compare their effects. Second, the vibration conditions were defined based on previous studies and the NATO regulations [64] for normal computer operations. The exposure time for each vibration condition was not as long enough as experienced in practice. Such experimental settings could account for the non-significant influence of vibration on visual search performance as severe or long-term vibration conditions may severely affect individuals' performance [20, 65]. Therefore, our findings may not be generalizable to severe or long-term vibration scenarios or other vibration directions (e.g., up-and-down vibration and omnidirectional vibration), which merits further investigations. Third, we examined only one typical interface characteristic (i.e., color scheme) among various interface characteristics (e.g., target size and density) and environmental factors (e.g., brightness and illuminance). These factors could be jointly examined to reflect visual search performance and perceptions in more realistic practical scenarios than those examined in this study.

6. Conclusions

We investigated the effects of visual fatigue and color scheme on visual search performance in three vibration conditions in several types of visual search tasks. Vibration did not affect visual search performance but it did affect mental workload and perceived task difficulty. Thus, in vibration conditions (e.g., on vehicles), operators may need to implement various strategies to reduce their mental workload. It is also necessary to minimize visual fatigue, given its proven negative influence on visual search performance and perceptions. Color schemes must be appropriately selected to enhance visual search performance and decrease mental workload and discomfort perception. These findings can serve as valuable guidance for the design of visual search interfaces for application in operating environments exposed to vibrations.

Conflicts of Interests
The authors of this manuscript have no potential conflicts of interest to disclose.

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