

Effects of Time Pressure and Task Difficulty on Visual Search

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Abstract The process of pilot constantly checking the information given by instruments was examined in this study to detect the effects of time pressure and task difficulty on visual searching. A software was designed to simulate visual detection tasks, in which time pressure and task difficulty were adjusted. Two-factor analysis of variance, simple main effect, and regression analyses were conducted on the accuracy and reaction time obtained. Results showed that both time pressure and task difficulty significantly affected accuracy. Moreover, an interaction was apparent between the two factors. In addition, task difficulty had a significant effect on reaction time, which had a linearly increasing relationship with the number of stimuli. By contrast, the effect of time pressure on reaction time was not so apparent under high reaction accuracy of 90 % or above. In the ergonomic design of a human-machine interface, a good matching between time pressure and task difficulty is key to yield excellent searching performance.

Keywords Visual search · Time pressure · Task difficulty · Reaction time · Accuracy

1 Introduction

In the future, tactical aircrafts are predicted to operate in a significantly more demanding environment than they do today. With the advancements in aviation science and technology, tactical aircrafts have been enhanced with advanced features, particularly the display interface of aircraft cockpits [1]. An aircraft cockpit is a highly complex human-machine interaction system, and its display interface is

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one of the most essential devices for pilot–aircraft interaction. Given the increased requirements for flight altitude, speed, and endurance time, as well as the automation of display systems, all tasks related to flight are now being concentrated on only one or a few pilots to accomplish. Such responsibilities cause tremendous physiological and psychological pressure on pilots. Consequently, ergonomics problems have become critical factors that restrict flight security [2, 3]. Data analysis of reasons for space flight failures indicated that 70–80 % of such cases were ascribed to the poor design of human-machine interfaces [4]. Cognitive compatibility is an important aspect in the design of the aircraft display interfaces. In other words, the structure of a human-machine interface should match the cognitive structures of its operators [5].

Vision is the key cognitive sensory channel of humans to interact with the world around them. Approximately 80 % of the perceived information is obtained through a person's vision [4]. Information detection tasks are an essential part of a human-machine system, and these activities invariably involve visual search [6]. In visual detection tasks during flight, the central nervous system and visual organ of pilots often suffer from strain as a result of focusing too much attention on the aircraft's operation process, which consists of continuous information gathering, analysis, judgment, and issuing commands, among others, ultimately causing visual and central nervous system fatigue [7]. Therefore, the work efficiency and flight safety of pilots and aircrafts largely depend on the matching degree between the visual display interface and the visual cognition characteristics of humans [8, 9]. Thus, the visual cognition of human operators should be examined to develop an optimized pilot–aircraft display interface [10, 11].

Aside from monitoring environmental changes, pilots must be aware of the situation of the aircraft itself while conducting missions. Numerous system parameters, such as performance, input, and work condition parameters, among others, are obtained from the display instruments. Pilots must monitor the target instruments by visually searching the instrument clusters constantly, and on the basis of which, they must render judgment and perform appropriate operations. However, the number of cockpit instruments has significantly increased with the improvement of aircraft performance; thus, the task difficulty of visual detection had also increased accordingly. Although electro-optic display systems have been widely applied and have played a significant role in reducing the number of display instruments, the task difficulty remains unresolved [12]. As such, pilots tend to feel pressure to act quickly, as time is a critical factor in the visual search process during missions. The pressure brought about by the time limit and the task difficulty largely affects the physiology and psychology of pilots, which may lead to a degraded search performance [13, 14]. The same situation exists in many other human-machine systems.

Existing ergonomic studies on aircraft display interfaces have mostly focused on coding information, such as character, symbol shape, size, color, background, luminance, and contrast; these works have helped improve the efficiency of identifying and improving the interface layout by visual area zoning [15–17]. Other works have explored the mental workload and situation awareness of operators [18, 19].

However, limited studies are available on visual search characteristics. As displays have increased in variety and complexity, the study of target visual detection tasks is becoming an increasingly popular research topic. The more accurate is the reaction of people to the target information in the time available, the more efficient the search would be. Therefore, an effective and efficient visual detection task should be designed to understand the factors involved in the visual search process and their relationships to the search performance.









This study developed a software to simulate the target visual detection task display in human-machine systems. The search performance of the subjects was then examined by setting different time pressure and task difficulty levels. These processes would provide scientific bases for the ergonomic design of a human-machine display interface, particularly for aircrafts.

2 Material and Method

2.1 Subject

A total of 10 college students from the Beijing University of Aeronautics and Astronautics, comprising six males (60 %) and four females (40 %), voluntarily participated in this experiment. Their ages ranged from 20 to 28 years old. They all have normal or corrected to normal visual acuity. Most of the subjects often spent between two and eight hours a day using personal computers for various purposes. None of them have had any experience with this type of experiment. All of the subjects were right-handed and were capable of flexibly using a mouse.

2.2 Apparatus and Software

The experiment for the visual detection task was conducted using a custom-made software developed on Visual Studio 2010. The software was run on a desktop computer with a 15-inch resolution (1280 × 1024 pixels) and luminance (68 cd/m²) display monitor (Fig. 1). Figure 1 shows that the middle gray region on the software interface is for the visual search picture, and the symbols represent different virtual instruments in the human-machine system. Among these symbols , denotes the target stimuli, whereas , , , , ,  and  represent different distractive stimuli. The parameter values of display time and number of stimuli, which includes both target stimuli and distractive stimuli, are both adjustable. The display time refers to the presentation time of each search picture. The visual search picture is divided into $n \times n$ small squares, with each square containing an instrument symbol. Therefore, the number of stimuli can be changed by adjusting the n -value. In the experiment, the different display times represented

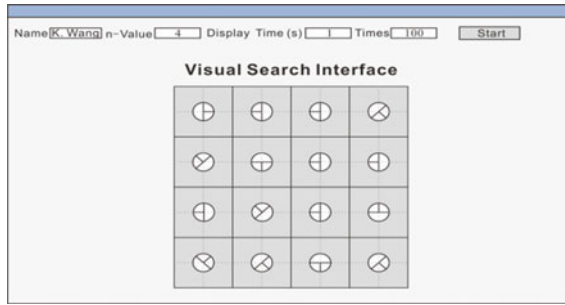


Fig. 1 Sample interface for visual detection task. Display time = 1 s. Number of stimuli = 16 (n-value = 4). Changing times of search picture = 100. All stimuli are refreshed and arranged randomly once the search picture changes. Each picture has at most only one target stimuli (appearance probability is 50 %), but two or more of the same distractive stimuli can appear simultaneously

different levels of time pressure, whereas the different numbers of stimuli represented different levels of task difficulty. The visual search picture changes once at a specified time interval. The symbols randomly appear in the different squares of the picture. Each search picture has two situations: “having a target” or “not having a target.” The probability of each situation is 50 %.

When the experiment begins and the search pictures appear, the subjects have to execute the following relevant actions:

- I. If the target is discovered, then the left button of the mouse should be pressed immediately.
- II. If the user is certain that there is no target by visual searching, then the right button of the mouse should be pressed immediately.
- III. If the user is unsure as to whether a target is present within the specified time, then no mouse button should be pressed.

After the experiment, the software automatically records the accuracy and reaction time.

2.3 Experiment Condition Control

In the visual field of anthropology, different space positions led to different search performances [20]. Therefore, to avoid any influence in the experiment, the visual search picture was placed in the optimum visual working area of the screen, and its size and position were kept constant. When different n-values were selected to divide the search picture, only the small square number was changed. In other words, the number and density of stimuli were changed, and the task difficulty changed with the change in n-value. The experiment was conducted under an

undisturbed environment with good illumination. To decrease the influence of fatigue in the experiment, the subjects can freely adjust their sitting posture, mouse placement, and screen angle.

3 Procedure

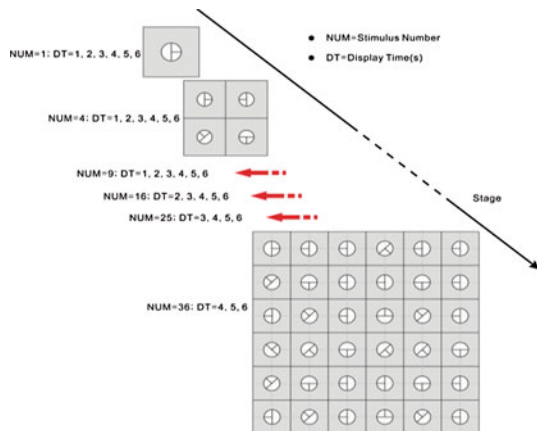
3.1 Pre-experiment

The pre-experiment adopted 6×6 a within-subjects design. To ensure experiment rationality and data volume, three subjects were randomly selected to participate in the pre-experiment. Different values of display time (1, 2, 3, 4, 5, 6/s) and number of stimuli (1, 4, 9, 16, 25, 36) were set. The valid range of display time and number of stimuli in this study were determined in consideration of the human factors, such as visual perception, mental workload, and so on. The actual experiment was divided into six stages because of its long duration (approximately 4 h in total); each stage consisted of several blocks that depend on the different values of display time and number of stimuli (Fig. 2). Each subject was given three days, with two stages per day, to complete the experiment. Such an arrangement avoids the effect of fatigue on search performance.

3.2 Actual Experiment

The subjects were required to familiarize themselves with the experimental process and train in advance. Before each block, the person conducting the experiment had to set the display time, n-value (number of stimuli = $n \times n$), and the number of

Fig. 2 Experimental design. The entire experiment is divided into six stages according to the different numbers of stimuli. Each stage consisted of several blocks that depend on the different display times. The entire experiment consists of 30 blocks, which require approximately 4 h to finish. All values of display time and the numbers of stimuli are based on the results of the pre-experiment



search pictures changed (each block in this study is set 100 times) in advance. To begin the block, the subjects had to stare at the center of the visual search region, where a red “+” symbol was displayed. They would then click “Start,” which was displayed on the screen, by pressing the mouse button. The stimuli were displayed on the center of the screen once the subject clicked “Start.” Memorizing the target symbol, the subjects were asked to scan the search picture by visual searching, and then react as quickly and as accurately as possible. After the first search picture disappeared, another one immediately appeared, with the stimuli being rearranged at random. To avoid lower motivation to engage in deep, deliberate, and systematic processing of information, the subjects under the time-pressure condition were told that they are on a tight schedule and reminded at intervals during the task to “hurry up” and “work harder”. When the block was finished, the accuracy and reaction time during this process were recorded by using a computer. The subjects can then make adjustments and rest.

3.3 Performance Measures

Search performance was investigated by assessing the accuracy and reaction time to complete a detection task. In this study, time pressure and task difficulty were considered the two main factors that affect the search performance. For statistical testing, two-factor ANOVA was performed using SPSS 19.0.

4 Results

4.1 Effects of Display Time and Number of Stimuli on Accuracy

The results shown in Table 1 were obtained by analyzing the data using two-factor ANOVA in which display time and number of stimuli are the two factors. This analysis indicates that the effects of both display time and number of stimuli on accuracy are significant (for display time: $F = 157.2$, $P < 0.05$; and for number of stimuli: $F = 140.166$, $P < 0.05$). This analysis also indicates that an interaction is apparent between display time and number of stimuli ($F = 18.069$, $P < 0.05$). Simple main effect analysis was then conducted by programming based on within-subject factor experiment. Table 2 shows that display time significantly differed at different levels of number of stimuli (all $P < 0.05$), whereas number of stimuli significantly differed at different levels of display time (all $P < 0.05$).

Figure 3 was constructed using number of stimuli as abscissa and accuracy as ordinate. For each given display time, the search accuracy shows a downtrend with the number of stimuli. However, the decrease in the amplitude of the curves differs

Table 1 Effect analysis of accuracy at different display times and number of stimuli

Source	Sum of squares	df	F	P
Display time	65414.3	5	157.2	0.0
Number of stimuli	58309.5	5	140.2	0.0
Display time * number of stimuli	28563.1	19	18.1	0.0

Table 2 Simple effect analysis between different display times and number of stimuli

Source	Sum of squares	df	F	P
Display time VS.1	729.93	5	12.0	0.0
Display time VS.4	29483.73	5	189.3	0.0
Display time VS.9	39520.00	5	199.9	0.0
Display time VS.16	59497.33	5	212.9	0.0
Display time VS.25	57287.53	5	210.5	0.0
Display time VS.36	54765.40	5	110.6	0.0
Number of stimuli VS.1s	59584.80	5	266.1	0.0
Number of stimuli VS.2s	73105.13	5	522.4	0.0
Number of stimuli VS.3s	416126.93	5	272.0	0.0
Number of stimuli VS.4s	16900.33	5	47.9	0.0
Number of stimuli VS.5s	9238.73	5	24.8	0.0
Number of stimuli VS.6s	3478.40	5	12.2	0.0

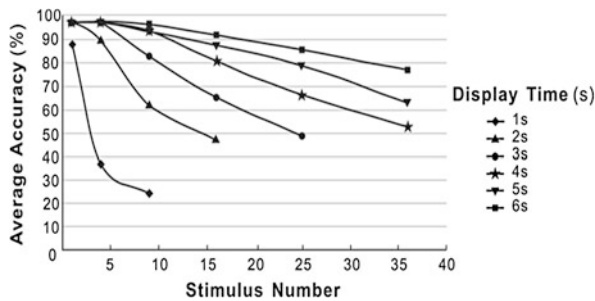


Fig. 3 Number of stimuli/accuracies at different display times. The general trend of accuracy decreases with the increase in the number of stimuli in visual searching. However, the decrease in the amplitude of the curves differs for different display times. A longer display time corresponds to a smaller effect of the number of stimuli on visual search accuracy

for different display times. By using nonlinear regression analysis, the functions of curve fitting were derived with high fitting coefficients, as shown in Table 3. All curves are expressed in quadratic equations. To a certain extent, there are $|y6'| < |y5'| < |y4'| < |y3'| < |y2'| < |y1'|$, which indicates that a longer display time corresponds to a smaller effect of the number of stimuli on visual search accuracy.

Table 3 Regression functions of reaction accuracy at different display times

Display time(s)	Optimal approximation function	R2
1	$y_1 = 108 - 25.62x + 1.81x^2$	1.00
2	$y_2 = 105.01 - 5.53x + 0.113x^2$	0.98
3	$y_3 = 102.3 - 2.31x + 0.003x^2$	0.998
4	$y_4 = 100.29 - 1.08x - 0.008x^2$	0.983
5	$y_5 = 98.28 - 0.37x - 0.017x^2$	0.996
6	$y_6 = 97.69 - 0.18x - 0.012x^2$	0.992

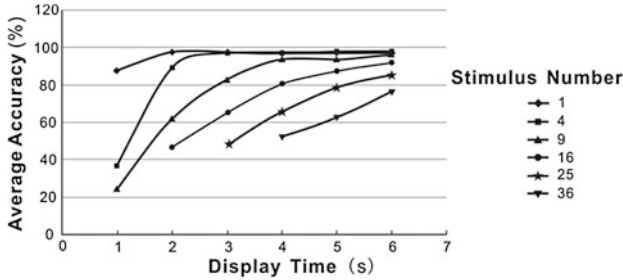


Fig. 4 Display time/accuracies at different number of stimuli. The curves show that accuracy tends to initially increase and then tends to stabilize. However, several small decreases in accuracy can be observed in the stable section (e.g., stimuli number = 1, display time = 3 s; number of stimuli = 9, display time = 5 s)

Moreover, this result also verifies the interaction between display time and number of stimuli.

Figure 4 shows the display time/accuracy curves for different numbers of stimuli. The curves show that accuracy tends to initially increase and then tends to stabilize. Several small decreases in values can be observed in the middle section. For example, in the single stimuli discrimination task with only one stimuli symbol appearing each time, the search accuracy is significantly low when the display time is 1 s. The reason is that the display time is too short, thereby causing a high level of time pressure. In addition, errors occur in the process because the subjects cannot follow the pace of the search picture switching in terms of using the eyes and implementing the operations. Accuracy is stable at approximately 98 % when the display time reaches 2 s or longer. Moreover, accuracy reaches the maximum when the display time is 3 s but is slightly lower when the display time continues to increase. The reason is that the presentation time of each search picture is too long; thus, the subjects spread their attention easily during the blocks. The same rules are applied in the multi-stimuli discrimination task. Table 4 shows the data of the maximum number of stimuli and optimum number of stimuli that can be discriminated at different display times under accuracy of 90 % or above. Figure 5 shows the comparisons between the display time and the maximum number of stimuli with a linear regression line, a correlation coefficient ($R^2 = 0.9365$), and a

Table 4 Relative number of stimuli threshold at different display times

Display time(s)	Maximum number of stimuli	Optimum number of stimuli
2	1	1
3	4	1
4	9	4
5	9	4
6	16	4

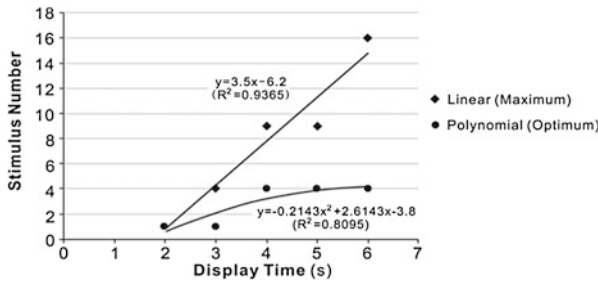


Fig. 5 Regression relationship between display time and maximum/optimum number of stimuli. Comparison between the display time and the maximum number of stimuli with a linear regression line ($R^2 = 0.9365$), and comparison between the display time and the optimum number of stimuli with a polynomial fitting curve ($R^2 = 0.8095$)

linear fitting equation ($y = -6.2 + 3.5x$). If $x = m$, the number of stimuli N only satisfies the condition $N \leq 3.5m - 6.2$, and a good search performance can be obtained. The polynomial fitting curve between the display time and the optimum number of stimuli is also presented in Fig. 5, with a correlation coefficient ($R^2 = 0.8095$), which suggests that the optimum number of stimuli is not directly proportional to the display time. Therefore, in the design of a human-machine interface, the best matching of display time and number of stimuli is necessary.

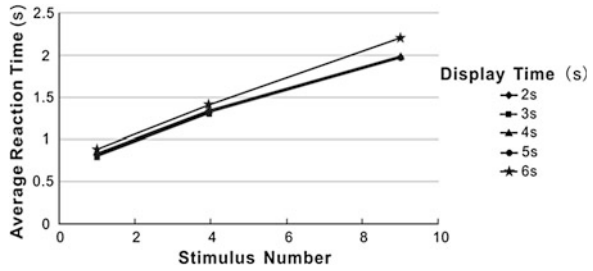
4.2 Effects of Display Time and Number of Stimuli on Reaction Time

Inherent connection and trade-off exist between reaction speed and accuracy [21]. The study of reaction speed is meaningless when reaction accuracy is too low. If the matching between the display time and the number of stimuli exceeds the normal scope of human visual cognition, then it will lead to low accuracy. Therefore, the influence of display time and number of stimuli on reaction time is analyzed in this study under accuracy of 90 % or above. Table 1 shows the related reaction time data. Two-factor ANOVA was conducted, and the results are shown in Table 5.

Table 5 Effect analysis of reaction time at different display times and number of stimuli

Source	Sum of squares	df	F	P
Display time(s)	0.313	4	1.4	0.226
Number of stimuli(s)	23.171	2	213.1	0.000
Display time * number of stimuli	0.118	5	0.4	0.823

Fig. 6 Number of stimuli/reaction time at different display times. Reaction time increases linearly with the increase in the number of stimuli



The main effect of display time on reaction time is insignificant ($F = 1.438$, $P > 0.05$), whereas the main effect of number of stimuli is significant ($F = 213.132$, $P < 0.05$). The interaction between display time and number of stimuli is insignificant ($F = 0.435$, $P > 0.05$).

With the use of the reaction time data in Table 1, the curves with display time and number of stimuli were designated as abscissa and accuracy as ordinate (Figs. 6 and 7). Figure 6 shows that reaction time increases linearly with the increase in number of stimuli. By conducting linear regression analysis, functions of curve fitting were derived with high fitting coefficients, as shown in Table 6. The four functions were considered comprehensively, with each additional stimuli extending the reaction time by 154 ms. Figure 7 shows that the mean reaction time remains generally stable despite the increase in display time in the visual search task with the same number of stimuli. However, the reaction time of several subjects was found to slightly increase with the increase in display time. The reason is that the

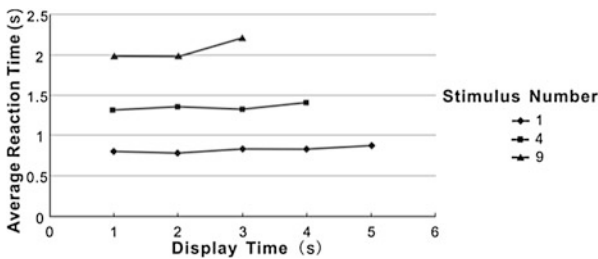


Fig. 7 Display times/reaction times at different number of stimuli. Mean reaction time remains generally stable despite the increase in display time in the visual search task with the same number of stimuli

Table 6 Regression function of reaction accuracy at different display times

Display time (s)	Optimal approximation function	R ²
3	$y = 0.621 + 0.171x$	1.000
4	$y = 0.73 + 0.143x$	0.995
5	$y = 0.721 + 0.141x$	0.996
6	$y = 0.732 + 0.164x$	0.999

display time was too long for the subjects, causing lower time pressure. The inattention of the subjects leads to longer reaction time.

5 Discussion

In this study, different display times represent different levels of time pressure, whereas different numbers of stimuli represent different task difficulties. The experimental results revealed that the effects of display time and number of stimuli on accuracy were both significant at the 0.05 level. Moreover, their interaction was also significant; that is, the two factors may work together on visual search accuracy. Simple main effect analysis revealed that the display time significantly differed at different levels of the number of stimuli; and that number of stimuli significantly differed at different levels of display time. The highest reaction accuracy in the search task would be obtained when the two factors reach the best matching.

Under the given time pressure, accuracy decreases as a result of the increase in the number of stimuli. The gradual development process can be described, as follows: (1) judge correctly and operate correctly; (2) judge correctly but operate wrongly or have no time to operate; (3) judge wrongly and the operation falls behind; (4) brain response cannot keep up with the changing search pictures and has no time to judge. For the given number of stimuli, accuracy increases as the time pressure decreases, and then tends to stabilize after reaching a certain point. Before that point, wrong judgments and operations easily resulted because of limitations in cognizing capacity, physiology, and emotion, among others, of the advanced nerve center caused by higher pressure [22]. When such point is reached, time pressure had no significant effect on accuracy. However, a slight rebound phenomenon was noted among several subjects. This phenomenon was due to their excessive relaxation, which caused wrong judgments and operations [23].

The current study analyzed the effects of display time and number of stimuli on reaction time under high accuracy because inherent connection and trade-off exist between reaction speed and accuracy. The results indicated that the main effect of display time on reaction time was insignificant, whereas the effect of the number of stimuli was significant. When the time pressure was given, the reaction time was linear with number of stimuli; this finding is inconsistent with the theory of log proposed by Merkel (1885) [24]. The two reasons for such difference are as follows:

(1) the stimuli material was different, which led to a different task difficulty; (2) the two situations of “having target” and “not having target” were considered one case without distinction. However, such consideration would not affect the visual search law in the current study.

6 Conclusion

In this study, the effects of time pressure and task difficulty on visual search were studied during a simulated visual detection task. As expected, task difficulty demonstrated a significant effect not only on search accuracy but also on reaction time. Time pressure exhibited a significant effect only on search accuracy. Moreover, their integrated effect on search accuracy is very significant. Therefore, the two factors should be comprehensively considered when designing a human-machine interface, particularly the dashboard design. Instrument number and cognitive difficulty should be decided reasonably based on the order of importance and urgency of instrument monitoring tasks and cognitive characteristics of humans. For instruments that need an immediate reaction, the dashboard should be designed with little search difficulty by reducing the number of instruments or other measures. Time pressure is relative with task difficulty; thus, the best matching of time pressure and task difficulty can produce good search performance.

Although several valuable findings involving visual search laws were obtained, several limitations were also noted in this study. First, the number of participants in the experiment was small because of the long course. Second, except for time pressure and task difficulty, other factors, such as target location, were not considered in the experiment, which also has effects on search performance. Third, the task difficulty was not only related to number of stimuli but also related to the shape and size characteristics of the stimuli [25]. Finally, in the actual human-machine systems, there are always more than one target in the visual detection tasks. In future studies on visual search laws, all of these factors should be considered to guide the ergonomic design of human-machine interfaces.

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