Axiomatic design principles in analysing the ergonomics design parameter of a virtual environment

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A B S T R A C T
One of the negative side effects experienced by users when interacting with virtual environment is visual symptoms. This paper explores the ergonomics design parameters of the virtual environment to minimize such negative side effect by applying axiomatic design principles. Axiomatic design is a method to provide a systematic way for designing products and large systems. The independence axiom is used to map customer domain (CAs) to functional domain (FRs) and physical domain (DPs). A paper based survey was conducted to identify and define customers’ preference in the virtual environment. A virtual robot manufacturing system was developed as a case study to explore ergonomic design parameters that satisfy the independence of FRs and CAs. Results of this study shows that the ergonomic design parameters of virtual environment identified (DP161-DP162-DP121-DP111-DP131-DP141-DP151-DP152) have satisfied the independence functional requirement and desired visual comfort for users. By uncoupling the design it provides an efficient and effective sequence of design activities FR161-FR162-FR121-FR111-FR131-FR141-FR151-FR152.

Relevant to industry: Result of this study contributes a guide for designer in implementing the design parameter to design the virtual environment.

1. Introduction

Virtual environment (VE) can be defined as a computer generated three dimensional model environment in which a user feels as if he/she is present in it and the user can interact intuitively with objects contained within it (Wilson, 1999). While being advantageous in experiencing new environment without having to build the real thing, the experience comes with some side effect for some. When interacting with VE through output and input devices, it has been reported that some users experienced negative side effects by being immersed into the graphically rendered virtual world. One of the side effects is known as cyber sickness i.e. especially affecting the vision (Stanney et al. 1998; Barret, 2004). Stanney et al. (1998) further mentioned that for VEs to be effective and well received by their users; while avoiding unwanted side effect, human being's limitation needs to be considered during the VE design stage. It is highly essential to ensure that advances in VE technology will not be at the expense of human well-being.

Ergonomics is a branch of science that is concerned with the achievement of optimal relationship between workers and their work environment (Tayyari and Smith, 1997). Since human being’s limitation is crucial in the design process of a virtual environment, implementation of ergonomics will bring about an optimal VE experience for users. Good design incorporating ergonomics consideration will enhance the communication between the user and the virtual world. Since several ergonomic factors contribute to good VE design, there is a need to investigate what are the critical ergonomics design parameters.

Ergonomics research related to virtual environment has been conducted in the past, but the focus of the research is only on the use of VE as a tool in ergonomics analysis (Shaikh et al., 2004; Colombo and Cugini, 2005; Pappas et al., 2005; Dukic et al., 2007; Hu et al., 2011). Shaikh et al. (2004) studied on participatory ergonomics using VR and found that VR system will help towards designing better workplaces. Colombo and Cugini (2005) researched on virtual humans and prototypes, evaluating ergonomics and safety. While Pappas et al. (2005) investigated on
In recent years, there have been quite a number of researches on the application of AD in ergonomics whether theoretical or empirical studies. In a theoretical study, Helander (1995) had conceptualized the use of AD procedures in ergonomics. Suh (2007) proposed the application of AD and complexity theory in ergonomics design to improve the robustness and efficiency of design. In an empirical study, Quill et al. (2001) applied AD to design visual information. Helander and Lim (2002) introduced AD as a foundation in ergonomics design where they designed an ergonomics microscope workplace and biomechanical design of hand tools. Lo and Helander (2007) conducted a study to analyse the complexity in human-machine system and develop a methodology for eliminating the couplings. Helander (2007) also conducted a study to identify the sources of coupled and proposed new design parameters that uncoupled the design in human-machine interaction. However, there have been no researches on the application of AD to the identification of ergonomics design parameter of a VE. Thus, the objective of this study is the identification of the ergonomics design parameter for designing a Virtual Environment using axiomatic design.

2. Research method

Three main activities were undertaken in this study to explore the design parameters of a virtual environment based on ergonomics principles using axiomatic design theory. The following research activities are:

Activity 1: Investigating the major attributes that a customer is looking for in the virtual environment through a survey.

Activity 2: Performing an empirical study to analyse the effect of VE attributes on visual symptoms.

Activity 3: Applying Axiomatic Design to the design of a virtual environment based on the data collected and analysed in activities 1 and 2.

2.1. Survey

A questionnaire was developed and deployed to respondents who are familiar with the virtual world. It consists of three parts that are the personal background (part A), user criteria of the VE design (part B), and user criteria of the VE’s hardware used. A paper based survey was conducted in a period of 3 months to identify attributes that customer are looking for in a VE. It is called the voice of the customer. Over one hundred questionnaires were distributed in the survey. The required sample size is determined as minimum valid feedback responses. Descriptive non-parametric statistical analysis was also applied in this study.

2.2. Empirical study

The objective of the empirical study is to analyse the effect of virtual environment attributes on visual symptoms. The experiments were conducted at the ergonomic-virtual reality laboratory. Eight university students participated in the study where none of the participants suffered from any vestibular and visual dysfunction and were not taking any medication during the experiments. The mean age was 21.7 years old (aged 19–23 years). A sitting position was adopted with the subject sitting at a distance of 15–25 cm from the back edge of the table to complete the task. The activity is to operate a virtual robot in the VE using an infrared mouse (wireless mouse) with the motion observed on the wide screen display. The virtual stimulus system used is a virtual robot manufacturing system. It presents a virtual robot activity for storage loading and unloading (SLU) process (shown in Fig. 1).

A qualitative assessment was conducted through the use of questionnaire. The questionnaire was developed to identify the visual symptoms of the virtual environment variables/attributes investigated. The questionnaire consists of two principal parts. The first part contains the questions with seven response option. This is aimed to identify the visual problems experienced during or after interacting with the VE. The second part contains questions to identify the level of symptoms experienced based on the answers of the previous part. The answers to the questions in the second part were of the ordinal data type.

Non parametric statistical analysis was implemented involving descriptive statistic and statistical binomial test. The tests were on hypotheses about the effect of each attributes or variables of the virtual environment on the incidence of visual symptoms. The hypotheses developed were:

- H1: Colour of background has effect of visual symptoms among immersive environment users
- H2: Virtual lighting has effect of visual symptoms among immersive environment users
- H3: Contrast ratio has effect of visual symptoms among immersive environment users
- H4: Field of View (FOV) has effect of visual symptoms among immersive environment users
- H5: Flow rate (FR) has effect of visual symptoms among immersive environment users
- H6: Speed of virtual object motion has effect of visual symptoms among immersive environment users

![Fig. 1. Snap shot of Virtual Robot Manufacturing System.](image-url)
• H7: Resolution of display has effect of visual symptoms among immersive environment users

The level of significance was set at $\alpha = 0.05$ for all analyses.

2.3. Application of axiomatic design

Design involves a continuous interplay between “what we want to achieve” and “how we want to achieve it” (Suh, 1990, 2001). According to Suh (2001), a concept domain constitutes an important foundation of axiomatic design approach (AD) to systemize the thought process involved in this interplay. This concept creates demarcation lines between four different kinds of design activities that embody the customer domain, which are the CAs (customers attributes) for a design; the functional domain, which are the FRs (functional requirements) that satisfy the CAs; the physical domain, which are the DPs (design parameters) that satisfy the FRs; and the process domain, which are the PVs (process variables) to produce the design specified in term of the DPs.

In the mapping process from domain to domain, Suh (2001) recommends it must be done within a “solution-neutral environment”. This means that mapping must be defined without ever thinking about something that has already been designed. Once the CAs had been identified and defined, this attributes must be translated into FRs and map them into a specific DPs satisfying the FRs and also into PVs that can satisfy the DPs specified. This process began as one to many processes in a hierarchy way, that it is also called zigzag or decomposition process, by referring to two axioms: the independence axiom (axiom 1) and the information axiom (axiom2).

Axiom 1 states that the independence of FRs must always be maintained. It means that the design solution must be such that each of the FRs is not affected by the others FRs. Thus a correct set of DPs has to be selected to satisfy the FRs that maintains the independence (Suh, 2001). This mapping process can be formulated mathematically as (Suh, 2001)

$$\{\text{FR}\} = [A]\{\text{DP}\}$$

where $[A]$ is a design matrix that relates FRs and DPs. There are three types of design matrices as shown in Fig. 2 that are uncoupled design, decoupled design, and coupled design. The uncoupled design is an ideal design which each of the DPs controls only one of the FRs. This matrix is often called the diagonal matrix (Fig. 2 (a)). When the independence of FRs cannot be satisfied by an uncoupled or diagonal matrix, the independence of FRs can be met if and only if the DPs are determined in a proper sequence. Such a design is called a decoupled design or a triangular matrix (Fig. 2 (b)). In accordance with Suh (2001), when a matrix produces a coupled design or a full matrix (Fig. 2 (c)) then it may result with many problems in design. Therefore the coupled design is not robust and cannot survive random variations of DPs. To satisfy the independence axiom, Suh (2001) suggested that the design matrix must be the diagonal matrix or triangular matrix.

Axiom 2 states that the design with the smallest information content is the best design among those designs that satisfy the Independence Axiom (Suh, 2001). In this research, axiom 2 is not considered since it is not being the objective of this research. Moreover, only axiom 1 is needed to develop the design parameters of the virtual environment based on ergonomics principles.

3. Results and discussion

3.1. Effect of the virtual environment attributes on visual symptoms

Table 1 shows the results of experiment and statistical binomial test on the effect of the virtual environment attributes on visual symptoms. At 5% significant level, the test results in all hypotheses being accepted. Thus it can be concluded that the design of a virtual environment is influenced by several attributes such as virtual colour background, virtual lighting, contrast ratio, field of view, flow rate, speed of virtual object, and type and resolution of display.

These attributes significantly affect users particularly with eyestrain symptoms. Blurred vision symptoms are significantly affected by several attributes of the VE design i.e. the red colour of the background, the field of view (FOV), the speed of virtual object motion, and the contrast ratio at $-50.83\%$. Dry and irritated eyes symptoms are also significantly affected by several attributes of the VE design i.e. the virtual lighting at 10% and 100% levels of brightness, field of view (FOV) for all conditions, flow rate (FR) for all conditions, the speed of virtual motion for all speeds, the resolution of CRT screen at medium and low resolution and a contras ratio of 0%. Virtual lighting at 100% level of brightness significantly affects visual symptoms, particularly light sensitivity symptoms of the users.

3.2. Independence ergonomic design parameters

3.2.1. Voice of customer on the VE characteristics

Sample size required at 5% significant level and 10% precision or accuracy level is 49 samples. And as many as 105 questionnaires have been accepted as valid feedback responses. It means that number of sample received has fulfilled the minimum requirement of valid samples size. Results of the descriptive non parametric analysis on 105 valid responses produced several customers’ attributes of the virtual environment design. These are CA1: “Desired visual comfort when using the virtual environment (86.67%)”, CA2: “Using a virtual environment must be user friendly (93.33%)”, CA3: “Less effort in using the virtual environment (53.33%)”, CA4: “Interesting in seeing the virtual environment (93.33%) and CA5: “Easy to change the virtual environment when used (80%)”. The highest possible relevant CAs with a minimum negative effect on vision was analysed and selected. The analysis resulted in that customer needs a visual comfort when interacting with the virtual environment. Thus CA1 is a customer attribute that was most relevant with minimum negative effect on vision and will be considered further in this study.

3.2.2. Mapping process of the FRs to DPs

In the mapping process, the identified customer attribute, CA1, was translated to functional requirement (FR1). Thus, the FR1 to satisfy CA1, which is “Desired visual comfort when using the

\[
\begin{align*}
\text{FR}_1 &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}, \\
\text{FR}_2 &= \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}, \\
\text{FR}_3 &= \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}
\end{align*}
\]

(a)

\[
\begin{align*}
\text{DP}_1 &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}, \\
\text{DP}_2 &= \begin{bmatrix} 1 & 1 & 0 \end{bmatrix}, \\
\text{DP}_3 &= \begin{bmatrix} 1 & 1 & 1 \end{bmatrix}
\end{align*}
\]

(b)

\[
\begin{align*}
\text{FR}_4 &= \begin{bmatrix} 1 & 1 \end{bmatrix}, \\
\text{FR}_5 &= \begin{bmatrix} 1 & 1 \end{bmatrix}, \\
\text{FR}_6 &= \begin{bmatrix} 1 & 1 \end{bmatrix}
\end{align*}
\]

(c)

Fig. 2. Three types of the design matrix; (a) uncoupled design, (b) decoupled design, (c) coupled design.
Table 1
Results of experiment and binomial test of visual symptoms.

<table>
<thead>
<tr>
<th>No.</th>
<th>Observation Proportion [%]</th>
<th>Symptoms</th>
<th>Exact Sig. (1-tailed)</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Colour</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1. Red</td>
<td>75</td>
<td>Eye strain</td>
<td>0.633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>63</td>
<td>Blurred Vision</td>
<td>0.321</td>
</tr>
<tr>
<td>2</td>
<td>Fuchsia</td>
<td>63</td>
<td>Eye strain</td>
<td>0.321</td>
</tr>
<tr>
<td>3</td>
<td>Dark Sky Blue</td>
<td>63</td>
<td>Eye strain</td>
<td>0.321</td>
</tr>
<tr>
<td>4</td>
<td>Medium Slate Blue</td>
<td>63</td>
<td>Eye strain</td>
<td>0.321</td>
</tr>
<tr>
<td>5</td>
<td>White</td>
<td>75</td>
<td>Eye strain</td>
<td>0.633</td>
</tr>
<tr>
<td>Level of Brightness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10% level</td>
<td>83</td>
<td>Eye strain</td>
<td>0.534</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Dry and Irritated Eyes</td>
<td>0.114</td>
</tr>
<tr>
<td>7</td>
<td>25% level</td>
<td>83</td>
<td>Eye strain</td>
<td>0.534</td>
</tr>
<tr>
<td>8</td>
<td>50% level</td>
<td>83</td>
<td>Eye strain</td>
<td>0.534</td>
</tr>
<tr>
<td>9</td>
<td>100% level</td>
<td>100</td>
<td>Eye strain</td>
<td>0.178</td>
</tr>
<tr>
<td></td>
<td></td>
<td>67</td>
<td>Dry and Irritated Eyes</td>
<td>0.138</td>
</tr>
<tr>
<td>Ratio of Contrast</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-50.83%</td>
<td>75</td>
<td>Eye strain</td>
<td>0.633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>63</td>
<td>Blurred Vision</td>
<td>0.321</td>
</tr>
<tr>
<td>11</td>
<td>-24.58%</td>
<td>75</td>
<td>Eye strain</td>
<td>0.633</td>
</tr>
<tr>
<td>12</td>
<td>0% (~0.56%)</td>
<td>75</td>
<td>Eye strain</td>
<td>0.633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Dry and Irritated Eyes</td>
<td>0.114</td>
</tr>
<tr>
<td>Degree of FOV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>FOV 120°</td>
<td>50</td>
<td>Eye strain</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Dry and Irritated Eyes</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>63</td>
<td>Dry and Irritated Eyes</td>
<td>0.321</td>
</tr>
<tr>
<td>14</td>
<td>FOV 85°</td>
<td>75</td>
<td>Eye strain</td>
<td>0.633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Blurred Vision</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Dry and Irritated Eyes</td>
<td>0.114</td>
</tr>
<tr>
<td>Flow Rate (FR)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Flow Rate 5 (FR5)</td>
<td>75</td>
<td>Eye strain</td>
<td>0.633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Dry and Irritated Eyes</td>
<td>0.114</td>
</tr>
<tr>
<td>16</td>
<td>Flow Rate 10 (FR10)</td>
<td>75</td>
<td>Eye strain</td>
<td>0.633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Blurred Vision</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Dry and Irritated Eyes</td>
<td>0.114</td>
</tr>
<tr>
<td>Level of Speed</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Low Speed</td>
<td>83</td>
<td>Eye strain</td>
<td>0.534</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Blurred Vision</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>67</td>
<td>Dry and Irritated Eyes</td>
<td>0.466</td>
</tr>
<tr>
<td>18</td>
<td>High Speed</td>
<td>75</td>
<td>Eye strain</td>
<td>0.633</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Blurred Vision</td>
<td>0.114</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>Dry and Irritated Eyes</td>
<td>0.114</td>
</tr>
<tr>
<td>Level of Resolution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>High Resolution</td>
<td>56</td>
<td>Eye strain</td>
<td>0.166</td>
</tr>
<tr>
<td>20</td>
<td>Medium Resolution</td>
<td>89</td>
<td>Eye strain</td>
<td>0.300</td>
</tr>
<tr>
<td>21</td>
<td>Low Resolution</td>
<td>56</td>
<td>Eye strain</td>
<td>0.166</td>
</tr>
<tr>
<td>CRT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>High Resolution</td>
<td>67</td>
<td>Eye strain</td>
<td>0.399</td>
</tr>
<tr>
<td>23</td>
<td>Medium Resolution</td>
<td>67</td>
<td>Eye strain</td>
<td>0.399</td>
</tr>
<tr>
<td></td>
<td></td>
<td>56</td>
<td>Dry and Irritated Eyes</td>
<td>0.166</td>
</tr>
<tr>
<td>24</td>
<td>Low Resolution</td>
<td>67</td>
<td>Eye strain</td>
<td>0.399</td>
</tr>
<tr>
<td></td>
<td></td>
<td>56</td>
<td>Dry and Irritated Eyes</td>
<td>0.166</td>
</tr>
</tbody>
</table>

*p > 0.05; N = 8.*
For a good design the corresponding third level DP to satisfy the third level independence FR can be developed as follows:

\[
\begin{align*}
\text{DP}_{111} &= \text{Medium Slate Blue, Dark Sky Blue, Fuchsia} \\
\text{DP}_{121} &= 25\%–50\% \text{ of brightness} \\
\text{DP}_{131} &= 24.58\% \text{ of contrast} \\
\text{DP}_{141} &= 85 \text{ or } 120 \text{ degrees of FOV} \\
\text{DP}_{151} &= \text{Five second per piece of flow rate} \\
\text{DP}_{152} &= \text{High or low speed of motion} \\
\text{DP}_{161} &= \text{LCD} \\
\text{DP}_{162} &= \text{High or low resolution}
\end{align*}
\]

### 3.2.3. Analysis of independence of the design

To maintain the independence axiom, the design matrix must be either diagonal/uncoupled or triangular/decoupled (Suh, 1990, 2001). The design equation (2) describing the relationship between FR and DP at the second level is given by

\[
\begin{align*}
\text{FR}_{11} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{FR}_{12} &= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \end{bmatrix} \\
\text{FR}_{13} &= \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \end{bmatrix} \\
\text{FR}_{14} &= \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix} \\
\text{FR}_{15} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{FR}_{16} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\text{DP}_{11} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \\
\text{DP}_{12} &= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \\
\text{DP}_{13} &= \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \\
\text{DP}_{14} &= \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix} \\
\text{DP}_{15} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{DP}_{16} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}
\end{align*}
\]

The equation presents a decoupled design or upper triangular design matrix where each FR is satisfied by a DP. Even if there are a few of the FRs affecting the other FRs, the design is still acceptable. However such design activities are rather difficult to complete due to the difficulty of designing the smooth virtual colour of the background (\text{DP}_{11}) previously to meet \text{FR}_{11} before selecting the smooth display and compatible resolution (\text{DP}_{16}) and setting no glare and dark of \text{DP}_{12} of virtual lighting. This equation exhibits the existence of complexity in design. Thus a proper sequence of design activities should be developed such that a smooth display and compatible resolution (\text{DP}_{16}) and no glare and dark of virtual lighting (\text{DP}_{12}) should be satisfied first so that it can eliminate the complexity. The design equation (3) shows uncoupled design or diagonal design matrix at the second level where it is independent each other. This is an ideal design that it should be achieved.

\[
\begin{align*}
\text{FR}_{11} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{FR}_{12} &= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \end{bmatrix} \\
\text{FR}_{13} &= \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \end{bmatrix} \\
\text{FR}_{14} &= \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix} \\
\text{FR}_{15} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{FR}_{16} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\text{DP}_{11} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix} \\
\text{DP}_{12} &= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \end{bmatrix} \\
\text{DP}_{13} &= \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \end{bmatrix} \\
\text{DP}_{14} &= \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix} \\
\text{DP}_{15} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{DP}_{16} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}
\end{align*}
\]

Hereafter the relationship between FR and DP at the third level that is presented in the design equation (4) is equal to at the second level where the design matrix is diagonal design matrix or uncoupled design. This shows the decomposition in the lower level is consistent with the higher level. The design equation (4) explains that the design activities begins firstly using Liquid Crystal Display (\text{DP}_{161}) to meet \text{FR}_{161} and followed by setting high or low resolution (\text{DP}_{162}) and setting 25%–50% of brightness (\text{DP}_{121}) in virtual lighting independently. Then the others independence DPs (\text{DP}_{111}, \text{DP}_{131}, \text{DP}_{141}, \text{DP}_{151}, \text{DP}_{152}) are the next design activities that should be conducted to satisfy the others independence FRs that are \text{FR}_{111}, \text{FR}_{131}, \text{FR}_{141}, \text{FR}_{151}, \text{and} \text{FR}_{152}.

\[
\begin{align*}
\text{FR}_{161} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{FR}_{162} &= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \end{bmatrix} \\
\text{FR}_{121} &= \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \end{bmatrix} \\
\text{FR}_{111} &= \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix} \\
\text{FR}_{131} &= \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix} \\
\text{FR}_{141} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{FR}_{151} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{FR}_{152} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
\text{DP}_{11} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix} \\
\text{DP}_{12} &= \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \end{bmatrix} \\
\text{DP}_{13} &= \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \end{bmatrix} \\
\text{DP}_{14} &= \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix} \\
\text{DP}_{15} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix} \\
\text{DP}_{16} &= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}
\end{align*}
\]

The diagonal design matrix presented in equations (3) and (4) for the second and third level shows that the sequence of design activity begins by specifying the corresponding \text{DP}_{161} of determining the LCD to meet the independent functional requirement \text{FR}_{161}. This is followed by \text{DP}_{162} and \text{DP}_{121} which are to set the high or low resolution of display and also the level of brightness. These design activities are carried out without affecting the others. And it facilitates a designer to work with the next design activities efficiently. Thus the sequence of the design activities should be \text{FR}_{161}+\text{FR}_{162}+\text{FR}_{121}+\text{FR}_{111}+\text{FR}_{131}+\text{FR}_{141}+\text{FR}_{151}+\text{FR}_{152}.

### 3.2.4. Analysis of the ergonomics design parameter

According to the International Ergonomics Association (2003), ergonomics (or human factors) is related to methods to design in order to optimize human wellbeing and overall system performance. In view of this, the system elements (in this context is the virtual environment) must be designed to address the needs, abilities, and limitations of users. But one of the fundamental problems is the multiple functional system-human compatibility requirements that must be satisfied at the same time (Karwowski, 2005). Suh (2007) proposed using axiomatics design theory to map human capabilities and limitations to system (technology-environment) requirements and affordances.

Results of the axiomatic design approach and ergonomics principles in this study show that the design parameters identified have satisfied the independence functional requirement (see design equation (3)). It was found that medium slate blue, dark sky
blue and fuchsia produced no visual symptoms compared to other colours. It was also found that the 25%–50% range level of brightness of virtual lighting caused only one visual problem with some users not experiencing any visual symptoms at all. The above findings indicate that the colour of the virtual background should be softer and the level of brightness should not produce the effect of glare so as to suit the ability and limitation of user’s vision.

A level of contrast of 24.58% between virtual object and background causes no symptoms on users’ vision. It also causes less visual symptoms. An 85 or 120° field of view has a similar effect on vision. This is because both FOVs did not produce any visual symptoms on more than 50% of the users. Thus the setting of the field of view is crucial in reducing visual problems. A 5 s per piece flow rate and high or low speed motion of virtual object set simultaneously can result in the reduction of visual disorders perceived by the users. Finally the use of liquid crystal display (LCD) with high or low resolution is the best choice because no problem with vision was encountered by more than 40% of the users. This is consistent with the result of Saito et al. (1993) and Menozzi et al. (1999).

4. Conclusion and recommendation

A reduction of symptoms on the user’s vision is a state that should be achieved when the design parameters of the virtual is able to address the needs, ability and limitations of the user. In this paper it has been shown that the design parameters developed on the basis of ergonomics principles by using the AD method can satisfy the desired visual comfort in the design of a virtual environment.

It can be concluded that:

1. The Axiomatic design approach is an efficient method to identify the ergonomics design parameter of a virtual environment
2. Uncoupled design provides a proper sequence of the design activities independently
3. The design of a virtual environment is influenced by several attributes such as colour background, virtual lighting, field of view, flow rate, speed of virtual object, and resolution of display and contrast ratio which may significantly affect users particularly with visual symptoms.
4. The design parameters of a virtual environment identified based on ergonomics criteria satisfying the independence functional requirement and the customer voice includes Medium slate blue, dark sky blue, fuchsia for smooth virtual colour of background, 25%–50% of brightness for appropriate level of virtual lighting, ±24.58% of good contrast between virtual object and background, 85 or 120 degrees of field of view (FOV) for good viewing, high or low speed of flow rate and motion virtual object for an appropriate motion, liquid crystal display (LCD) and high or low resolution of display for appropriate output devices.

Future research will include validating the design parameters.

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References


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