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The Effect of 3D TVs on Eye Movement and Motor Performance

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Abstract: Three-dimensional TVs have been commercialized in recent few years; however, poor visual and motor performances may have an impact on consumer acceptance of 3D TVs. The purpose of this study was to investigate the effects of 3D TVs on eye movement and motor performance. Specifically, the effect of stereoscopic display parallax of 3D TVs and movement task index of difficulty (ID) on eye movement was investigated. In addition, the effect of stereoscopic display parallax of 3D TVs and movement task ID on motor performance was also investigated. Twelve participants voluntarily participated in a multi-directional tapping task under two different viewing environments (2D TV and 3D TV), three different levels of stereoscopic depth (140, 190, 210 cm), and six different Index of Difficulty levels (2.8, 3.3, 3.7, 4.2, 5.1, 6.1 bit). The study revealed that environment had significant effects on eye movement time, index of eye performance, eye fixation accuracy, number of fixations, time to first fixation, saccadic duration, revisited fixation duration, hand movement time, index of hand performance, and error rate. Interestingly, there were no significant effects of stereoscopic depth on eye movement and motor performance; however, the best performance was found when the 3D object was placed at 210 cm. The main novelty and contributions of this study is the in-depth investigations of the effect of 3D TVs on eye movement and motor performance. The findings of this study could lead to a better understanding of the visual and motor performance for 3D TVs.

Keywords: 3D TV; stereoscopic displays; virtual reality; depth

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1. Introduction

Three-dimensional TVs have been commercialized in recent years. The objective of this commercialization is to replicate the experience achievable in 3D cinematic presentations in a more intimate home setting [1]. 3D TVs are affordable, aesthetically pleasing, and can provide users with a sense of presence [2]; therefore, the commercialization has been accompanied by the increasing availability of 3D TVs broadcast channels or even 3D home cinema [3]. Engineers and academicians are continually engaged in the assessment of 3D TV, aiming to maximize the image quality while also minimizing the side effects [4–6]. To fully optimize 3D TVs, it is necessary to gain a better understanding of the impact of 3D TVs on the Human Visual System (HVS) [3].

Three-dimensional TVs generate 3D images by creating depth. Depth, also widely known as parallax in 3D stereoscopic display [7,8], was defined as the binocular disparity in the human visual system that gives a 3D stereoscopic effect of depth with each eye receiving a similar image, but not identical, to that of a real spatial vision by horizontal disparity [9]. The user can experience the depth of 3D TVs by wearing 3D glasses [10]. Ideally, 3D TVs should be able to detect 3D glasses positions and change the depth immediately so the users can perceive the image comfortably [3].

One common device to evaluate the depth perception in the stereoscopic display is an eye tracker [2,7]. It has been extensively used to collect and analyze HVS in the stereoscopic display [11]. Eye trackers are able to capture the eye movement, which provides evidence of visual attention as a fundamental system in visual perception [12]. Eye trackers have been widely used in many research disciplines, such as measuring cognitive load during the driving task [13], assembly task [14], software screen complexity [15], and even military camouflage [16]. In the context of 3D interface design, an eye tracker has the potential to improve many existing 3D interaction techniques [2].

Despite the numerous papers related to 3D TVs in recent years, very limited research has investigated the effect of 3D TV environments on eye movement and motor performance. Most studies which utilized 3D TVs mostly only investigated the subjective assessment of visual discomfort. Read et al. [17] investigated the changes in vision, balance, and coordination associated with normal home 3D TVs viewing in the 2 months after first acquiring a 3D TV. Read [18] also investigated the subjective experience in-home 3D TVs over 8 weeks by using symptoms questionnaire, while Lambooij et al. [19] investigated the three different assessments for visual discomfort: (1) single assessment score for each stimulus sequence, (2) continuous assessment, and (3) retrospective assessment for the entire test. Similarly, Lee et al. [20] investigated the effect of stimulus width on visual discomfort by measuring visual discomfort and binocular fusion time, while Chang et al. [21] and Chang et al. [22] only examined the physical properties of 3D glasses. Furthermore, a more recent study by Zang et al. [23] compared the difference in visual comfort between 3D TVs and VR glasses. Finally, Urvoy et al. [24] proposed a comprehensive review of visual fatigue and discomfort based on physiological and psychological processes enabling depth perception.

Some of the most recent studies related to 3D TVs generally incorporated physiological responses of the human while watching the stimuli on a 3D TV. For instance, Chen et al. [25] investigated the effect of 3D TVs on human brain activity. In addition, Manshouri et al. [26] and Chen et al. [27] utilized EEG to investigate the effect of 3D TVs on brain waves. However, the effects of the 3D TVs on eye movements and motor performance are still clearly underexplored. Generally, poor visual and motor performances may have an impact to consumer acceptance of 3D TV. A further in-depth investigation of eye movement and motor performance are needed to enhance the performance in 3D TV.

Our previous studies investigated the effect of parallax on eye movement parameters in the projection-based stereoscopic display [8,28–30]. Eye movement parameters which consisted of eye movement time, fixation duration, time to first fixation, number of fixations, and eye gaze accuracy were evaluated under three different levels of depth. The results revealed that depth had significant effects on all eye movement parameters in projection-based stereoscopic displays [28,29]. The participants were found to have longer eye movement time, longer fixation duration, longer time to first fixation, larger number of fixations, and less eye gaze accuracy when the target was projected at 50 cm in front of the screen compared to projected at 20 cm in front of the screen or projected at the screen [28].

The purpose of this study was mainly intended to investigate the effects of 3D TV environments on eye movement and motor performance. Using a similar approach to our previous studies [8,28,29,31–33], we utilized an eye tracker to explore a comprehensive analysis regarding the effect of 3D TVs on selected eye movement parameters and motor performance. We also discussed the effect of depth and index of difficulty, since both variables could influence eye movement and motor performance in a stereoscopic environment [34]. This study is one of the first studies that investigated the effect of 3D TVs on eye movement and motor performance simultaneously. The findings of this study could lead to better understanding of the visual and motor performance for 3D TVs.

2. Materials and Methods

2.1. Participants

Twelve healthy graduate students (6 male and 6 female) from National Taiwan University of Science and Technology were voluntary participated in the current study (Mean: 25 years; standard deviation: 3 years). All participants reported normal or corrected to normal visual acuity (1.0 in decimal unit). Prior to the study, the participants were required to fill out a consent form and screened for the capability to see the 3D object clearly on a 3D TV.

2.2. Apparatus and Stimuli

A Tobii X2-60 eye tracker (Tobii, Stockholm, Sweden) was utilized to collect the eye movement data. The accuracy was 0.4 degrees of visual angle and the sampling rate was 60 Hz [22]. The screen recording media element from Tobii Studio cannot be applied in this experiment because we created the parallax setting of the 3D object from a 3D Vision IR Emitter NVIDIA. Therefore, a Logitech webcam C-920 (Logitech International S.A., Lausanne, Switzerland) was utilized to record the eye movement and eye fixation point on the screen display. This webcam was integrated with a Tobii eye tracker. All equipment was fixed using adhesive tape and marked. As recommended by Salvucci and Goldberg [35] and Goldberg [15], the raw fixation data were filtered using Velocity Threshold Identification (I-VT) and the velocity threshold was set to 30 o/s. Tobii Studio eye tracking version 3.3.2 was used for the analysis of raw fixation data. The entire experiment was conducted in a dark room (3.6 m × 3.2 m × 2.5 m) covered by dark curtains and walls to create an excellent stereoscopic environment.

During the experiment on a 3D stereoscopic display, participants sat at a distance of 60 cm in front of the Tobii Eye Tracker (Figure 1). In addition, a Sony 3D TV Bravia was placed at 210 cm distance from the participant's eyes. All participants were instructed to wear active 3D glasses to perceive the 3D environment by utilizing a pair of Sony TDG-BT500A (Sony Group Corporation, Tokyo, Japan). These Sony 3D glasses were integrated with a 3D TVs Sony Bravia (ViewSonic PJD6251 DLP) (Sony Group Corporation, Tokyo, Japan) and a 3D Vision IR Emitter NVIDIA which adapted the 3D TV system with depth image-based rendering [36].

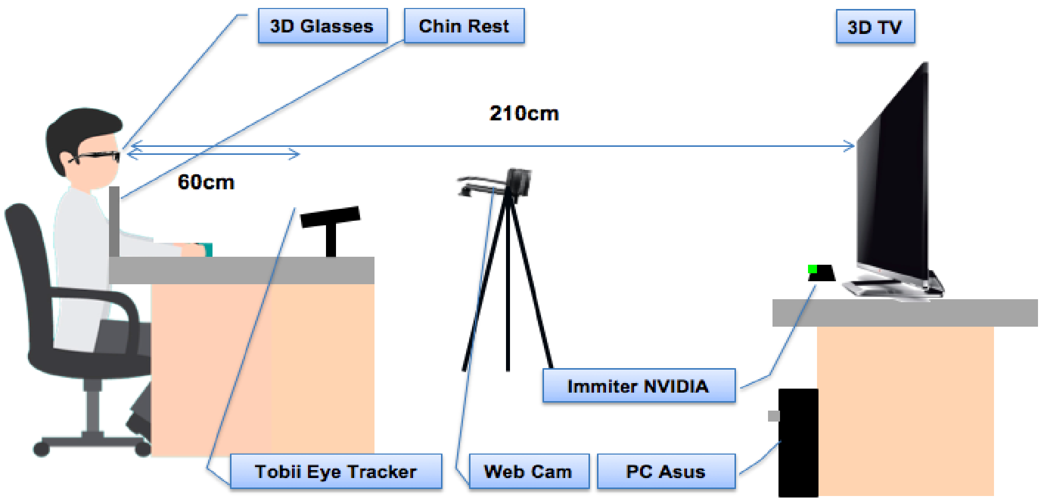

Figure 1. An illustration of the current study.

2.3. Independent Variables

Similar to [18], the environment was designed with two different levels: a 2D and 3D environment (Figure 2). In the 2D environment, the participant performed the tapping task on the screen display. In the 3D environment, participant performed the multidirectional tapping task; 3D TVs were integrated with NVIDIA to create a stereoscopic viewing environment.

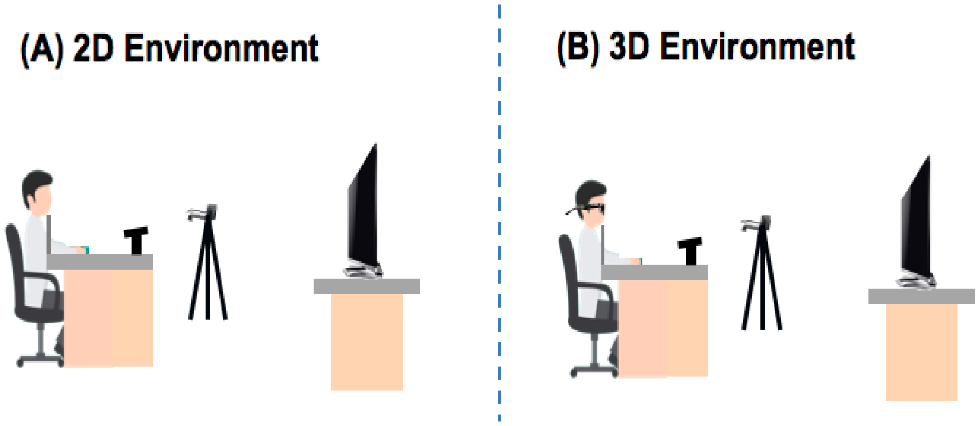

Figure 2. The illustration of two different environments. (**A**) Participant performed tapping task in a 2D environment. (**B**) Participant utilized 3D glasses to perform the multi-directional tapping task in a 3D environment. 3D TVs were integrated with NVIDIA to create a stereoscopic viewing environment.

The depth was varied into three levels: 210 cm, 190 cm, and 140 cm (Figure 3). The term "depth" was preferred over "parallax" in this study because we compared the effect of a 2D and 3D environment. In the 2D environment, we did not create a binocular disparity that creates a 3D effect. Thus, the participant asked to move closer to the screen in order to create an equal target distance as the experiment in the 3D environment (Figure 4).

The index of difficulty (ID) was defined as the task difficulty and precision level measured by object width and movement distance [37]. The unit of index of difficulty consisted of bits that equated to a quantity of information transmitted to measure the difficulty of the pointing tasks. This was explained that the pointing reduced due to higher information processing task. Following our previous publications [8,28,29] and ISO 9241-9, which classified precision task to measure the accuracy into three levels, i.e., low, medium, and high, ID and task precision level are presented in Table 1. There were two levels of environment, three levels of depth, and six levels of ID in the current study. Thus, we adopt a within-subject design with 36 combinations.

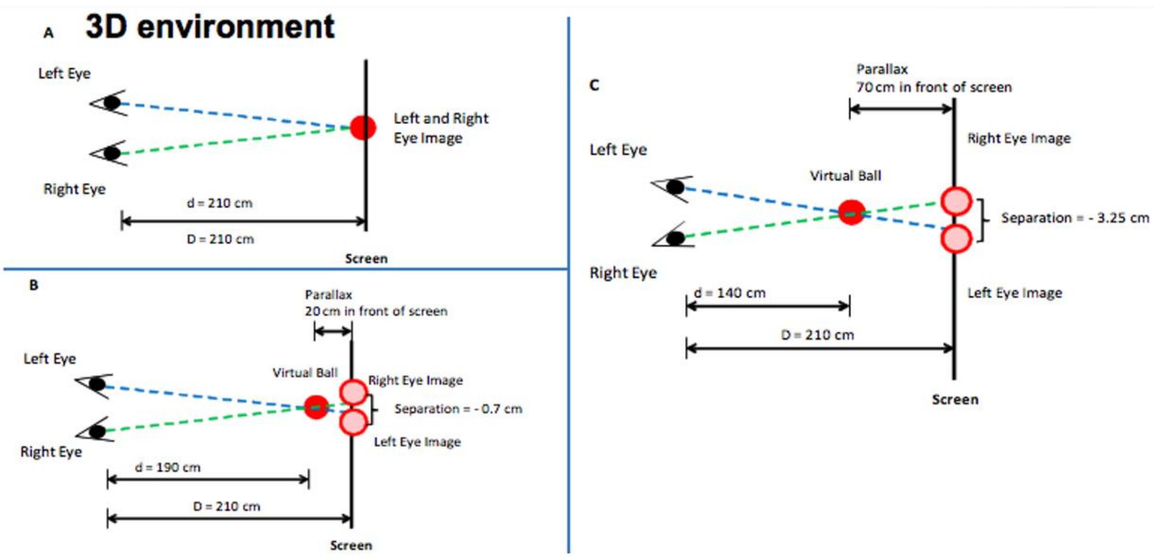

Figure 3. An illustration of the horizontal separation of two images on a 3D TV with three different levels of depth [5].

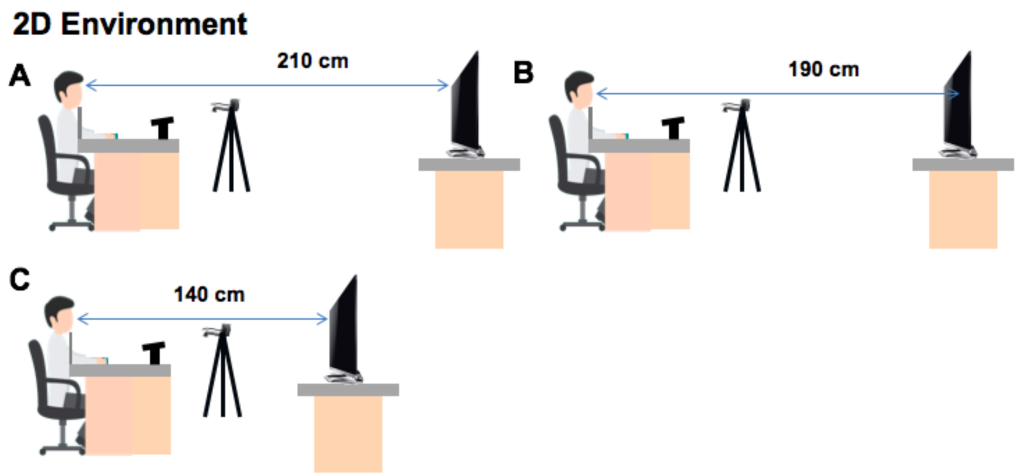

Figure 4. Participant performed the experiment in a 2D environment with distances of (**A**) 210 cm, (**B**) 190 cm, and (**C**) 140 cm.

Table 1. ID and task precision level [8].

Distance (Unity Unit)	Width (Unity Unit)	ID (Bits)	Task Precision Level
40	3.3	3.7	Low
40	2.3	4.2	Medium
40	0.6	6.1	High
20	3.3	2.8	Low
20	2.3	3.3	Low
20	0.6	5.1	Medium

2.4. Dependent Variables

Following two of our previous publications [8,28], there were two categories of dependent variables in the current study: eye movement and motor performance. The first category, eye movement, consists of eye movement time, index of performance eye, number of fixations, time to first fixation, saccade duration, revisited fixation duration, and eye gaze accuracy. The second category, motor performance, consists of hand movement time, index of performance hand, and error rate. The definition of each independent variables is presented in Table 2.

Table 2. Dependent variables and each definition.

Category	Variable	Definition	Supported by
Eye Movement	Eye movement time (EMT)	The elapsed time from the fixation point of the eye on the starting ball to the fixation point on the destination ball.	Lin & Widyaningrum [8]
	Index of eye performance (IP eye)	ID/EMT. IP eye shows the global index of eye performance, which considers speed and accuracy.	MacKenzie [38]
	Number of fixations	A total number of fixations counted starting from the origin virtual to destination virtual ball.	Lin et al. [29]
	Time to first fixation	An elapsed time from the slide presentation until the first fixation on the virtual target.	Goldberg [15]
	Saccade duration	A sum of saccadic time spent within an AOI.	Lin & Widyaningrum [8]
	Revisited fixation duration	A sum of revisited fixation durations within an AOI.	Lin & Widyaningrum [8]
	Eye gaze accuracy	The distance between the recorded fixation locations and the actual location of the projection of the image as a performance evaluation. The *x*-axis was measured from left to right and the *y*-axis was measured from bottom to the top.	Lin & Widyaningrum [28]

Table 2. *Cont.*

Category	Variable	Definition	Supported by
Motor Performance	Hand movement time (HMT)	Time taken from the starting ball to the destination ball.	Lin & Widyaningrum [8]
	Index of hand performance (IP hand)	ID/HMT. IP hand shows the global index of hand performance, which considers speed and accuracy.	MacKenzie [38]
	Error rate	A click outside the target ball. Since the total number of clicks was 12, the error rate was calculated as: Error rate = (N − 12)/12.	Lin et al. [34]; Lin & Widyaningrum [8]

2.5. Experimental Procedure

The current study was conducted according to the ethical guidelines published by National Taiwan University Research Ethics Committee. Prior to the experiment, participants were required to perform a visual acuity test and stereo vision check. The visual acuity of each participant was measured by utilizing a Snellen test [39]. In addition, each participant was also required to pass a stereo vision check to ensure that they were capable of perceiving the 3D target. Finally, they were required to fill out a consent form which consisted of confidential data of the participants and the detailed descriptions of experimental tasks.

During the experiment on 3D display, participants were asked to wear the Sony 3D glasses and sit on an adjustable chair. In addition, all participants were also to keep their head on a chin rest. At the beginning of the experiment, a calibration was performed for each participant to ensure that Tobii eye tracker detected the participant's eye movement. Regular calibration setting with five red dots from Tobii eye tracker was used as a default to capture participants' eye gaze binocularly. They were instructed to look at the five red calibration dots as accurately as possible until each red dot disappeared. The qualifying participants were included in the experiment.

A multidirectional tapping task was selected as a task in this study, as suggested by ISO 9241-9. Similar to our previous studies [28–30], participants were instructed to perform a tapping task by clicking 12 virtual balls in concentric circles with a mouse as fast and accurate as possible (Figure 5). The virtual red ball was programmed on the Unity 3D platform version 4.3.4 and projected as a 3D object.

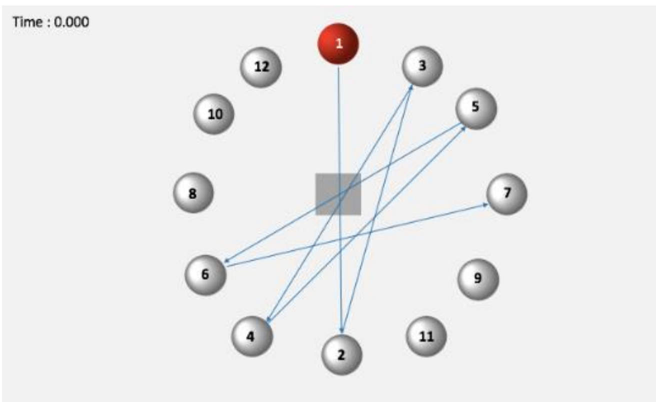

Figure 5. The pointing sequence of virtual red balls during multidirectional tapping task (shown as ball 1) [8].

Note that the ISO 9241-9 tapping task is performed on a 2D plane. Although visually the targets are displayed in 3D, the movement is on a plane. This situation is common for interactions in a 3D visual environment, where 3D input devices are not necessarily available or only planar movements are involved, such as pointing between menu items [2]. In this study, we used a desk mouse to tap between the targets, and therefore, the hand movement was limited to 2D motion. The cursor of the mouse is displayed in 3D but only moves on the vertical display plane, because the actual mouse moves on the horizontal desk plane. The mapping is a very common practice with the usual desktop computer setup. No additional learning is necessary. The effect under investigation, if any, would only come from the 3D visual display of the targets and the cursor, and would not be confounded with the effect of 3D movement of the cursor, which would be a much more complex interaction situation and is not within the scope of this study.

At the beginning, the 3D cursor was set at the center cube. To start the experiment, each participant was asked to click the center cube. One virtual red ball would appear at a time and participant was instructed to hit the virtual red ball by utilizing 3D cursor. After the red ball was hit, the color would turn white and the next virtual red ball would appear in red. Figure 5 shows the sequence of the virtual red ball. The changing color of the ball guided the participant to look at the balls in concentric circles until all 12 balls were clicked. Each participant completed all six levels of ID in one of thhree depth conditions (140 cm, 190 cm, and 210 cm) under two different environments (2D TV and 3D TV).

2.6. Data Processing and Analysis

Hand movement time (HMT) was recorded based on the 3D cursor clicks in the tapping task. On the other hand, eye movement data needed to be analyzed by using our previous algorithm [8]. The index of eye performance (IP eye) and index of hand performance (IP hand) was calculated by dividing the ID by the movement time [38]. Therefore, while analyzing the effects of environment, depth, and ID on IP eye and IP hand, the ID was removed from the RM-ANOVA table, since there was a direct correlation between ID and IP.

The repeated measures analysis of variance (RM-ANOVA) was employed with $\alpha = 0.05$ to test the significance of each independent variables and its interactions to each dependent variable. In addition, the significance criteria were adjusted according to the sequential Bonferroni (Bonferroni–Holm) correction algorithm for multiple comparisons. We also conducted a post-hoc Tukey HSD test to analyze the differences occurred between pairs of group means in the RM-ANOVA analysis.

3. Results

3.1. Eye Movement

3.1.1. Eye Movement Time

Table 3 presents the means, SDs, ANOVA, and Tukey HSD test results of the eye movement time. The environment was found to have a significant effect on eye movement time ($F_{1,11} = 5.732$, p-value = 0.036). The Tukey HSD test showed a significant difference between hand movement time in screen displays and stereoscopic displays. Eye movement time increased when participants performed the tapping task in stereoscopic displays. There were no significant interactions between depth and eye movement time ($F_{2,22} = 1.372$, p-value = 0.385), even though the eye movement time increased when the object was close to participants' eyes. The main effect for the index of difficulty ($F_{5,55} = 65.138$, p-value = 0.001) was significant on eye movement time. The result of the repeated measures ANOVA reported that there was no significant difference in the interactions between the environment and depth ($F_{2,22} = 0.161$, p-value = 0.852), the environment and index of difficulty ($F_{5,55} = 2.219$, p-value = 0.065), parallax and ID ($F_{10,110} = 1.722$, p-value = 0.085), and the environment, depth, and ID ($F_{10,110} = 0.599$, p-value = 0.811).

3.1.2. Index of Eye Performance

The result of the repeated measures ANOVA in Table 4 reported that there were significant interactions between the index of eye performance and the environment ($F_{1,11} = 5.249$, p-value = 0.043). Moreover, the Tukey HSD showed a significant difference between screen and stereoscopic displays. However, there was no significant difference between depth and the index of eye performance ($F_{2,22} = 1.317$, p-value 0.288). The interaction between the environment and depth ($F_{2,22} = 1.364$, p-value = 0.277), interaction between depth and ID

($F_{10,110}$ = 1.520, p-value = 0.142), and the interaction between the environment, depth, and ID ($F_{10,110}$ = 0.789, p-value = 0.640) were not significantly different from the index of eye performance. However, the interaction between the environment and index of difficulty was significantly different ($F_{5,55}$ = 2.497, p = 0.041).

Table 3. Means, SDs, ANOVA, and Tukey HSD test results of eye movement time.

Eye Movement Time						
	Level	**Mean (s)**	**Group [a]**	**SD**	$F_{n,m}$	***p*-Value**
Environment	2D Screen Displays	0.474	A	0.185	$F_{1,11}$ = 5.732	p = 0.036
	3D Stereoscopic Displays	0.635	B	0.334		
Depth	210 cm	0.525	A	0.260	$F_{2,22}$ = 1.372	p = 0.385
	190 cm	0.566	A	0.312		
	140 cm	0.571	A	0.269		
ID	2.8 bits	0.435	A	0.158	$F_{5,55}$ = 65.138	p = 0.001
	3.3 bits	0.479	B	0.262		
	3.7 bits	0.594	C	0.247		
	4.2 bits	0.580	C	0.225		
	5.1 bits	0.540	B, C	0.305		
	6.1 bits	0.699	D	0.374		
Environment * Depth					$F_{2,22}$ = 0.161	p = 0.852
Environment * ID					$F_{5,55}$ = 2.219	p = 0.065
Depth * ID					$F_{10,110}$ = 1.722	p = 0.085
Environment * Depth * ID					$F_{10,110}$ = 0.599	p = 0.811

Table 4. Means, SDs, ANOVA, and Tukey HSD test results of eye performance.

Index of Eye Performance						
	Level	**Mean (bits/s)**	**Group [a]**	**SD**	$F_{n,m}$	***p*-Value**
Environment	2D Screen Display	10.712	A	6.999	$F_{1,11}$ = 5.249	p = 0.043
	3D Stereoscopic Display	8.360	B	4.824		
Depth	210 cm	10.078	A	6.836	$F_{2,22}$ = 1.317	p = 0.288
	190 cm	9.665	A	6.361		
	140 cm	8.728	A	5.153		
Environment * Depth					$F_{2,22}$ = 1.364	p = 0.277

3.1.3. Number of Fixations

The main effect of the index of difficulty ($F_{5,55}$ = 15.022, p-value = 0.000) was significant for the number of fixations (Table 5). Post-hoc analysis with a Tukey HSD test revealed that there was a significant different when index of difficulty varied from low to high. The Tukey HSD test divided the index of difficulty levels into three groups as shown in Table 5. Similarly, the interaction of the environment and the index of difficulty was significantly different for number of fixations ($F_{5,55}$ = 3.171, p-value = 0.014). We did not find a significant difference in number of fixations for the environment ($F_{1,11}$ = 1.726, p-value = 0.216), depth ($F_{2,22}$ = 0.064, p-value = 0.938), interaction of the environment and depth ($F_{2,22}$ = 1.055, p-value = 0.365), interaction of depth and the index of difficulty ($F_{10,110}$ = 0.973, p-value = 0.471), and interaction of the environment, depth, and the index of difficulty ($F_{10,110}$ = 0.660, p-value = 0.759).

Table 5. Means, SDs, ANOVA, and Tukey HSD test results of number of fixations.

Number of Fixations						
	Level	**Mean**	**Group [a]**	**SD**	$\mathbf{F_{n,m}}$	***p*-Value**
Environment	2D Screen Displays	2.686	A	0.481	$F_{1,11} = 1.726$	$p = 0.216$
	3D Stereoscopic Displays	2.899	A	0.822		
Depth	210 cm	2.813	A	0.791	$F_{2,22} = 0.064$	$p = 0.938$
	190 cm	2.777	A	0.657		
	140 cm	2.745	A	0.583		
ID	2.8 bits	2.580	A	0.430	$F_{5,55} = 15.022$	$p = 0.000$
	3.3 bits	2.543	A	0.587		
	3.7 bits	2.883	B	0.449		
	4.2 bits	2.875	B	0.518		
	5.1 bits	2.627	A, B	0.871		
	6.1 bits	3.249	C	0.831		
Environment * Depth					$F_{2,22} = 1.055$	$p = 0.365$
Environment * ID					$F_{5,55} = 3.171$	$p = 0.014$
Depth * ID					$F_{10,110} = 0.973$	$p = 0.471$
Environment * Depth * ID					$F_{10,110} = 0.660$	$p = 0.759$

3.1.4. Time to First Fixation

Overall, the environment influenced time to first fixation ($F_{1,11} = 4.965$, *p*-value = 0.048). A longer time to first fixation occurred when a virtual target appeared on 3D TV displays (Table 6). Furthermore, the Tukey HSD test showed that time to first fixation on 2D TV screen displays differed from time to first fixation on a 3D TV. However, there was no significant difference between time to first fixation and depth ($F_{2,22} = 0.398$, *p*-value = 0.677), index of difficulty ($F_{5,55} = 0.408$, *p*-value = 0.841), interaction of environment and depth ($F_{2,22} = 0.392$, *p*-value = 0.681), interaction of environment and index of difficulty ($F_{5,55} = 0.853$, *p*-value = 0.518), interaction of depth and index of difficulty ($F_{10,110} = 1.365$, *p*-value = 0.206), and interaction of environment, depth, and index of difficulty ($F_{10,110} = 0.906$, *p*-value = 0.531).

Table 6. Means, SDs, ANOVA, and Tukey HSD test results of time to first fixation.

Time to First Fixation						
	Level	**Mean (s)**	**Group [a]**	**SD**	$\mathbf{F_{n,m}}$	***p*-Value**
Environment	2D Screen Displays	0.076	A	0.060	$F_{1,11} = 4.965$	$p = 0.048$
	3D Stereoscopic Displays	0.105	B	0.083		
Depth	210 cm	0.085	A	0.068	$F_{2,22} = 0.398$	$p = 0.677$
	190 cm	0.093	A	0.070		
	140 cm	0.096	A	0.083		
ID	2.8 bits	0.094	A	0.090	$F_{5,55} = 0.408$	$p = 0.841$
	3.3 bits	0.083	A	0.053		
	3.7 bits	0.090	A	0.063		
	4.2 bits	0.097	A	0.086		
	5.1 bits	0.088	A	0.077		
	6.1 bits	0.091	A	0.070		
Environment * Depth					$F_{2,22} = 0.392$	$p = 0.681$
Environment * ID					$F_{5,55} = 0.853$	$p = 0.518$
Depth * ID					$F_{10,110} = 1.365$	$p = 0.206$
Environment * Depth * ID					$F_{10,110} = 0.906$	$p = 0.531$

3.1.5. Saccadic Duration

The results of repeated measures ANOVA in Table 7 revealed that there were significant difference on the environment ($F_{1,11}$ = 8.481, *p*-value = 0.014), the index of difficulty ($F_{5,55}$ = 18.512, *p*-value = 0.000), interaction of the environment and depth ($F_{2,22}$ = 9.915, *p*-value = 0.001), interaction of depth and the index of difficulty ($F_{10,110}$ = 4.875, *p*-value = 0.000), and interaction of the environment, depth, and index of difficulty ($F_{10,110}$ = 2.047, *p*-value = 0.035). However, the analysis revealed there was no significant main effect for depth ($F_{2,22}$ = 1.271, *p*-value = 0.300) as well as for the index of difficulty ($F_{5,55}$ = 0.890, *p*-value = 0.494).

Table 7. Means, SDs, ANOVA, and Tukey HSD test results of saccadic duration.

Saccadic Duration						
	Level	**Mean (s)**	**Group [a]**	**SD**	$\mathbf{F_{n,m}}$	***p*-Value**
Environment	2D Screen Displays	0.535	A	0.182	$F_{1,11}$ = 8.481	p = 0.014
	3D Stereoscopic Displays	0.652	B	0.304		
Depth	210 cm	0.617	A	0.282	$F_{2,22}$ = 1.271	p = 0.300
	190 cm	0.581	A	0.256		
	140 cm	0.546	A	0.231		
ID	2.8 bits	0.436	A	0.173	$F_{5,55}$ = 18.512	p = 0.000
	3.3 bits	0.484	A	0.182		
	3.7 bits	0.665	B	0.220		
	4.2 bits	0.638	B	0.193		
	5.1 bits	0.613	B	0.286		
	6.1 bits	0.724	B	0.332		
Environment * Depth					$F_{2,22}$ = 9.915	p = 0.001
Environment * ID					$F_{5,55}$ = 0.890	p = 0.494
Depth * ID					$F_{10,110}$ = 4.875	p = 0.000
Environment * Depth * ID					$F_{10,110}$ = 2.047	p = 0.035

3.1.6. Revisited Fixation Duration

Repeated measures ANOVA in Table 8 results revealed that there was a significant main effect of the environment ($F_{1,11}$ = 6.122, *p*-value = 0.031), the index of difficulty ($F_{5,55}$ = 47.224, *p*-value = 0.000), and the interaction of environment and depth ($F_{2,22}$ = 12.463, *p*-value = 0.000) on revisited fixation duration. We have not found a significant difference between revisited fixation duration with depth ($F_{2,22}$ = 0.604, *p*-value = 0.556), interaction of the environment and the index of difficulty ($F_{5,55}$ = 1.955, *p*-value = 0.100), interaction of depth and index of difficulty ($F_{10,110}$ = 1.035, *p*-value = 0.419), and interaction of the environment, depth, and the index of difficulty ($F_{10,110}$ = 1.841, *p*-value = 0.062).

3.1.7. Eye Fixation Accuracy

The repeated measures ANOVA results in Table 9 shows that there was a significant difference between eye fixation accuracy in screen displays and stereoscopic displays ($F_{1,11}$ = 8.559, *p*-value = 0.014). Moreover, the Tukey HSD showed a significant difference between screen and stereoscopic displays. Similarly, it shows that there was a significant accuracy difference for six levels index of difficulty ($F_{1,11}$ = 13.799, *p*-value = 0.000). The Tukey HSD results divided six levels of index of difficulty into three groups (see Table 9). However, there were no significant accuracy differences between depth ($F_{2,22}$ = 2.131, *p*-value = 0.143), the environment and depth ($F_{2,22}$ = 4.785, *p*-value = 0.677), the environment and the index of difficulty ($F_{5,55}$ = 23.500, *p*-value = 0.620), depth and the index of difficulty ($F_{10,110}$ = 8.759, *p*-value = 0.928), and interactions of the environment, depth, and index of difficulty ($F_{10,110}$ = 28.604, *p*-value = 0.354).

Table 8. Means, SDs, ANOVA, and Tukey HSD test results of revisited fixation duration.

Revisited Fixation Duration						
	Level	**Mean (s)**	**Group [a]**	**SD**	$\mathbf{F_{n,m}}$	***p*-Value**
Environment	2D Screen Displays	0.974	A	0.274	$F_{1,11} = 6.122$	$p = 0.031$
	3D Stereoscopic Displays	1.114	B	0.401		
Depth	210 cm	1.027	A	0.358	$F_{2,22} = 0.604$	$p = 0.556$
	190 cm	1.042	A	0.341		
	140 cm	1.101	A	0.353		
ID	2.8 bits	0.762	A	0.216	$F_{5,55} = 47.224$	$p = 0.000$
	3.3 bits	0.947	B	0.234		
	3.7 bits	0.960	B	0.270		
	4.2 bits	0.967	B	0.265		
	5.1 bits	1.324	C	0.318		
	6.1 bits	1.303	C	0.388		
Environment * Depth					$F_{2,22} = 12.463$	$p = 0.000$
Environment * ID					$F_{5,55} = 1.955$	$p = 0.100$
Depth * ID					$F_{10,110} = 1.035$	$p = 0.419$
Environment * Depth * ID					$F_{10,110} = 1.841$	$p = 0.062$

Table 9. Means, SDs, ANOVA, and Tukey HSD test results of eye fixation accuracy.

Accuracy						
	Level	**Mean (%)**	**Group [a]**	**SD**	$\mathbf{F_{n,m}}$	***p*-Value**
Environment	2D Screen Displays	94.443	A	4.432	$F_{1,11} = 8.559$	$p = 0.014$
	3D Stereoscopic Displays	92.220	B	6.820		
Depth	210 cm	92.452	A	6.331	$F_{2,22} = 2.131$	$p = 0.143$
	190 cm	94.160	A	5.020		
	140 cm	93.383	A	6.036		
ID	2.8 bits	92.489	A	5.320	$F_{5,55} = 13.799$	$p = 0.000$
	3.3 bits	91.904	A	4.938		
	3.7 bits	96.071	B	5.772		
	4.2 bits	96.280	B	3.377		
	5.1 bits	90.098	A, C	5.248		
	6.1 bits	93.148	A	7.283		
Environment * Depth					$F_{2,22} = 4.785$	$p = 0.677$
Environment * ID					$F_{5,55} = 23.500$	$p = 0.620$
Depth * ID					$F_{10,110} = 8.759$	$p = 0.928$
Environment * Depth * ID					$F_{10,110} = 28.604$	$p = 0.354$

3.2. Motor Performance

3.2.1. Hand Movement Time

Table 10 presents the means, SDs, ANOVA, and Tukey HSD test of hand movement time. The mean average of hand movement time increased in stereoscopic displays. The ANOVA shows there is significant difference in the environment ($F_{1,11} = 15.879$, *p*-value = 0.002). The Tukey HSD test revealed a significant difference occurred between hand movement time in screen displays and stereoscopic displays. A longer hand movement time occurred with the object in stereoscopic displays. The mean of hand movement time increased with depth. When the object was close to participants' eyes, it resulted in a longer hand movement time. However, ANOVA results show that there is no significant difference for different depth level ($F_{2,22} = 0.996$, *p*-value = 0.385). The index of difficulty affected hand movement time ($F_{5,55} = 144.887$, *p*-value = 0.000). The result of the

Tukey HSD test reported a significant difference in index of difficulty (see Table 10). The ANOVA results revealed that a significant difference occurred between the interaction of the environment and depth ($F_{2,22}$ = 13.115, p-value = p = 0.000), interaction of environment and ID ($F_{5,55}$ = 3.177, p-value = 0.014), the interaction of the depth and index of difficulty ($F_{10,110}$ = 2.684, p-value = 0.003), and the interaction of the environment, depth, and ID ($F_{10,110}$ = 2.157, p-value = p = 0.026).

Table 10. Means, SDs, ANOVA, and Tukey HSD test results of hand movement time.

Hand Movement Time						
	Level	**Mean (s)**	**Group [a]**	**SD**	**$F_{n,m}$**	***p*-Value**
Environment	2D Screen Displays 3D Stereoscopic Displays	1.539 1.689	A B	0.371 0.451	$F_{1,11}$ = 15.879	p = 0.002
Depth	210 cm 190 cm 140 cm	1.594 1.617 1.673	A A A	0.388 0.399 0.467	$F_{2,22}$ = 0.996	p = 0.385
ID	2.8 bits 3.3 bits 3.7 bits 4.2 bits 5.1 bits 6.1 bits	1.160 1.403 1.602 1.572 1.881 2.068	A B C C D E	0.247 0.266 0.241 0.281 0.344 0.377	$F_{5,55}$ = 144.887	p = 0.000
Environment * Depth					$F_{2,22}$ = 13.115	p = 0.000
Environment * ID					$F_{5,55}$ = 3.177	p = 0.014
Depth * ID					$F_{10,110}$ = 2.684	p = 0.003
Environment * Depth * ID					$F_{10,110}$ = 2.157	p = 0.026

3.2.2. Index of Hand Performance

There was a significant main effect of environment and index of hand performance ($F_{1,11}$ = 22.317, p-value = 0.001) (Table 11). The Tukey HSD test reported significantly higher index of hand performance for screen displays. There was no significant effect of depth on the index of hand performance ($F_{2,22}$ = 1.53, p-value = 0.238). The Tukey HSD test showed a significant difference between each level of index of difficulty.

Table 11. Means, SDs, ANOVA, and Tukey HSD test results of index of motor performance.

Index of Hand Performance						
	Level	**Mean (bits/s)**	**Group [a]**	**SD**	**$F_{n,m}$**	***p*-Value**
Environment	2D Screen Display 3D Stereoscopic Display	2.772 2.539	A B	1.278 0.520	$F_{1,11}$ = 22.317	p = 0.001
Depth	210 cm 190 cm 140 cm	2.700 2.625 2.695	A A A	0.680 0.434 0.528	$F_{2,22}$ = 1.532	p = 0.238
Environment * Depth					$F_{2,22}$ = 13.207	p = 0.000

3.2.3. Error Rate

The repeated measures ANOVA results in Table 12 revealed a significant main effect of index of difficulty ($F_{5,55}$ = 9.920, p-value = 0.000) and interaction between the environment and depth ($F_{2,22}$ = 6.428, p-value = 0.006). However, there were no significant interactions between the environment ($F_{1,11}$ = 0.084, p-value = 0.777), depth ($F_{2,22}$ = 0.296, p-value = 0.747), the environment and index of difficulty ($F_{5,55}$ = 1.245, p-value = 0.301), depth and index of difficulty ($F_{10,110}$ = 1.683, p-value = 0.094), and the environment, depth, and index of difficulty ($F_{10,110}$ = 0.456, p-value = 0.915).

Table 12. Means, SDs, ANOVA, and Tukey HSD test results of index of error rate.

Error Rate						
	Level	Mean	Group [a]	SD	$F_{n,m}$	p-Value
Environment	2D Screen Displays	0.068	A	0.097	$F_{1,11}$ = 0.084	p = 0.777
	3D Stereoscopic Displays	0.070	A	0.099		
Depth	210 cm	0.065	A	0.086	$F_{2,22}$ = 0.296	p = 0.747
	190 cm	0.067	A	0.097		
	140 cm	0.073	A	0.111		
ID	2.8 bits	0.029	A	0.053	$F_{5,55}$ = 9.920	p = 0.000
	3.3 bits	0.050	A	0.068		
	3.7 bits	0.046	A	0.075		
	4.2 bits	0.053	A	0.074		
	5.1 bits	0.137	B	0.142		
	6.1 bits	0.097	C	0.107		
Environment * Depth					$F_{2,22}$ = 6.428	p = 0.006
Environment * ID					$F_{5,55}$ = 1.245	p = 0.301
Depth * ID					$F_{10,110}$ = 1.683	p = 0.094
Environment * Depth * ID					$F_{10,110}$ = 0.456	p = 0.915

Finally, Table 13 shows the experimental results summary in this study. This table represents all main effects of environment, depth, and index of difficulty on eye movement measures. In addition, Table 13 also shows the main effects of environment, depth, and index of difficulty on motor performance.

Table 13. Summary of the findings.

No	Dependent Variable	Environment	Depth	Index of Difficulty
1	Eye Movement Time (second)	p = 0.036, $F_{1,11}$ = 5.732	p = 0.385, $F_{2,22}$ = 1.372	p = 0.274, $F_{5,55}$ = 12.760
2	Index of Eye Performance (bits/second)	p = 0.043, $F_{1,11}$ = 5.249	p = 0.288, $F_{2,22}$ = 1.317	p = 0.000, $F_{5,55}$ = 11.353
3	Number of Fixations	p = 0.216, $F_{1,11}$ = 1.726	p = 0.938, $F_{2,22}$ = 0.064	p = 0.000, $F_{5,55}$ = 15.022
4	Time to first Fixation (second)	p = 0.048, $F_{1,11}$ = 4.965	p = 0.677, $F_{2,22}$ = 0.398	p = 0.841, $F_{5,55}$ = 0.408
5	Saccadic Duration (second)	p = 0.014, $F_{1,11}$ = 8.481	p = 0.300, $F_{2,22}$ = 1.271	p = 0.000, $F_{5,55}$ = 18.512
6	Revisited Fixation Duration (second)	p = 0.031, $F_{1,11}$ = 6.122	p = 0.604, $F_{2,22}$ = 0.556	p = 0.000, $F_{5,55}$ = 47.224
7	Eye Fixation Accuracy	p = 0.014, $F_{1,11}$ = 8.559	p = 0.677, $F_{2,22}$ = 13.799	p = 0.000, $F_{5,55}$ = 13.799
8	Hand Movement Time (second)	p = 0.002, $F_{1,11}$ = 15.879	p = 0.385, $F_{2,22}$ = 0.996	p = 0.000, $F_{5,55}$ = 144.887
9	Index of Hand Performance (bits/second)	p = 0.001, $F_{1,11}$ = 22.317	p = 0.238, $F_{2,22}$ = 1.532	p = 0.000, $F_{5,55}$ = 28.899
10	Error Rate (%)	p = 0.777, $F_{1,11}$ = 0.084	p = 0.747, $F_{2,22}$ = 0.296	p = 0.000, $F_{5,55}$ = 9.920

4. Discussion

4.1. The Effect of Environment (3D TV)

The result of a repeated measures ANOVA revealed that environment had significant effects on eye movement time, index of eye performance, time to first fixation, saccade duration, revisited fixation duration, eye gaze accuracy, hand movement time, and index of hand performance. However, there were no significant main effects of environment on number of fixations and error rate. Participants were found to have longer eye movement time, lower index of eye performance, longer time to first fixation, longer saccade duration, longer revisited fixation duration, lower eye gaze accuracy, longer hand movement time, and lower index of hand performance when the target was presented in a 3D environment.

Theoretically, eye movement should be faster than hand movement. Participants assured the position of the target until they decided to move their hand to click the target. Eyes will guide the hand to click target when the eyes fixate on the position of the target [40]. In this study, participants required a longer time to click the virtual target in the 3D environment compared with the target in the 2D environment. It appears that in the 2D environment, participants perceived the target clearly without any difficulty and confusion, and therefore, the participants could determine the target in screen displays faster and more effectively than the virtual target in the 3D environment.

The index of eye performance was higher than the index of hand performance because the extraocular muscles that shift the eye are the fastest muscle in the human body [41]. Therefore, the speed gain of the eye made a difference over the hand for the same distances and resulted a higher index of eye performance. Our study is consistent with [42], which reported that eye performance was much higher than hand click performance.

The index of hand and eye performances in the 3D environment was lower than in the 2D environment. This condition happened because the movement time in the 3D environment was longer than movement time in the 2D environment. The index of performance was the result of the index of difficulty divided by the movement time; therefore, a longer movement time would result in a lower index of difficulty.

In the 3D environment, participants had longer hand and eye movement times with a lower index of hand and eye performances. This condition might have been caused by the accommodation-vergence conflict when participants perceived a virtual target in the 3D environment [20,24,43]. This conflict might influence the binocular ability vision of participants to focus on the virtual target. Moreover, this conflict might have affected the speed and accuracy of the task [44].

Eye fixation accuracy declined when the participants performed in the 3D environment. Eye fixation accuracy was determined as the percentage deviation between eye fixation location and the projected images of the target in the 2D environment. Participants performed precisely when they perceived the target in the 2D environment. Participants encountered difficulty to fixate accurately on the projected images of the virtual target. High difficulty levels of cognitive processing might be a factor of lower accuracy in the 3D environment. Holmqvist et al. [11] stated that a microsaccade, an eye fixation movement tremor, and drift could happen due to a high difficulty level of cognitive processing. Moreover, low accuracy could have occurred because of perceived depth error [45]. Therefore, eye fixation accuracy became lower in the 3D environment.

A longer time to first fixation happened when participants performed in the 3D environment. This was not surprising since participants required more processing time in the 3D environment to recognize and to identify the location of the virtual ball. In order to perceived the virtual target clearly, participants needed longer eye adaptation and accommodation processes.

Based on the saccadic duration and revisited fixation duration, the results showed that saccadic duration and revisited fixation duration in the 3D environment were longer than those in the 2D environment. In the 3D environment, participants spent significantly more time in revisited fixation. Depth perception was required to perceive the virtual target in stereoscopic displays [46,47]. Difficulty to perceive the virtual target could affect the revisited fixation duration. Moreover, some participants reported that they found it more difficult to perceive the virtual target in the 3D environment compared to the 2D environment.

The error rate was not significantly different from the environment. Overall, the error rate calculation was below 7%. The results implied that there was no speed–accuracy tradeoff in this study. Therefore, the hand and eye movement results could be acknowledged as being truly an effect of the visual environment.

4.2. The Effect of Depth

The results of the repeated measures ANOVA revealed that there was no significant difference between depth and hand and eye movement times, the index of hand and eye performances, error rate, eye fixation accuracy, number of fixations, time to first fixation, saccadic duration, and revisited fixation duration. Even though the results showed no significant difference, there were trends in the results when participants performed the task in three different levels of depth.

Participants had longer eye movement time, longer hand movement time, longer saccadic duration, and longer revisited fixation duration when the target was presented closer to their eyes. Although depth was found not significantly affect most of the independent variables, the index of eye and hand performances were found lower at a depth of 140 cm compared to 190 cm and 210 cm. Moreover, participants had a higher error rate when the target was brought closer to the participants' eyes at a depth of 140 cm.

Psychophysical research reported that the implication of depth perception could affect human perception to see the target clearly. The compilation of experiment results about depth judgment reported misjudgment made by participants. They judged the depth distance to be smaller than the actual depth of target [48–51]. Therefore, depth could contribute to a longer hand and eye movement time, saccadic duration, and revisited fixation duration a lower index of hand and eye performance, and a higher error rate when the target projected closer to the participants' eyes.

4.3. The Effect of Index of Difficulty (ID)

The result of the repeated measures ANOVA reported that hand movement time, index of hand and eye performance, error rate, eye fixation accuracy, number of fixations, saccadic duration, and revisited fixation duration had a significant difference in six different levels of index of difficulty. However, there was no significant effect of index of difficulty on eye movement time and time to first fixation. Our previous study applied structural equation modeling (SEM) to analyze the interrelationship among ID and selected eye movement parameters [29]. We also found that ID had significant effects on eye movement time and number of fixations. In addition, we also revealed that ID had no significant effect on time to first fixation. Despite it being a different statistical technique, the repeated measures ANOVA analysis matches with the previous SEM analysis. Moreover, post-hoc analysis in one-way repeated ANOVA could reveal significant differences among the group which could not be obtained by utilizing an SEM analysis.

Hand and eye movement times increased when the index of difficulty increased. Similarly, saccadic duration and revisited fixation duration were longer when the index of difficulty level increased. Many researchers reported higher correlations between movement time and the index of difficulty [52–56]. Similarly, in this study, the index of difficulty significantly affected hand and eye movement time as well as saccadic duration and revisited fixation duration.

Hand and eye movement times were related to the index of hand and eye performance. The increase of movement time would be compensated for by the increase in the index of difficulty and decrease the value of the index of performance [38]. However, in this study, the results reported that participants had a higher index of hand and eye performances when they performed the tapping tasks at a higher level of index of difficulty. This occurred because of the slightly different in value between eye and hand movement times for each level of index of difficulty. Thus, the index of hand and eye performances would be high when the short movement time was divided by the high-level index of difficulty. Longer movement times have been consequently associated with the number of fixations [38]. In line with this study, longer movement times, caused by a higher level index of difficulty, lead to a higher number of fixations.

The index of difficulty influenced the error rate made by the participant in this experiment. Higher levels of index of difficulty caused a higher error rate and eye fixation accuracy. Wade et al. [57] and Card et al. [58] reported that decreasing target width caused a higher error rate. The smaller target width increased the difficulty level for the participants to perceive the target location, which would lead to an inaccuracy in the tapping task.

4.4. Practical Implications

Generally, poor visual and motor performances may have an impact on consumer acceptance of 3D TVs. This study provided a general implication for users to perceive virtual objects in 3D TVs or stereoscopic displays. The results revealed that poor visual and motor performances may have an impact on the acceptance of 3D TVs due to visual discomfort or fatigue. The variation of depth had no significant difference at different levels on any independent variable. The visual and motor performance was good in combination with depth in the experiment. However, the distance from the user to the display (3D TV) revealed that the depth of 210 cm had the best eye movement and motor performance compared with the distance (190 cm and 140 cm). The depth (210 cm) should minimize the vergence accommodation conflict for the users. In addition, the smallest depth (140 cm) would affect the visual phenomenon that occurs when the brain receives mismatching cues between vergence and accommodation of the eye. Thus, depth should be considered in order to minimize visual discomfort and vergence accommodation conflict.

4.5. Limiations and Future Research Directions

Despite the substantial contributions of this study, we would like to mention several limitations in this study. First, we purely investigated the effect of 3D TVs on eye movement and motor performance. Future research should propose a new technical solution to capture the physical and psychological changes simultaneously when a person watches a 3D TV. Second, the statistical analysis was RM-ANOVA, which could not investigate the effect of one independent variable on two or more dependent variables simultaneously. Future research that incorporates structural equation modeling or data mining techniques would be a promising direction. Finally, curved display TVs are currently becoming available on the market. Using our approach, future research could investigate the effect of curved display TVs on eye movement and motor performance.

5. Conclusions

Three-dimensional TVs have been commercialized in recent years; however, the commercialization of them has faced difficulties on the market. The purpose of this study was mainly to investigate in depth the effects of 3D TV environments on eye movement and motor performance. We also discussed the effect of parallax and index of difficulty, since both variables could influence eye movement and motor performance.

The results showed that the environment had significant effects on eye movement time, index of eye performance, eye fixation accuracy, number of fixations, time to first fixation, saccadic duration, revisited fixation duration, hand movement time, index of hand performance, and error rate. Participants were found to have longer eye movement time, lower index of eye performance, longer time to first fixation, longer saccade duration, longer revisited fixation duration, lower eye gaze accuracy, longer hand movement time, and lower index of hand performance when the target was presented in a 3D environment.

Interestingly, no significant effects of environment were found on the number of fixations and error rate. Regarding ID, the results showed that there were significant main effects between index of difficulty and hand movement time, index of hand and eye performances, error rate, eye fixation accuracy, saccadic duration, and revisited fixation duration. Finally, no significant differences were found between different levels of depth on any independent variables, although bigger depth (210 cm) mostly had the best eye movement and motor performance compared with smaller depth (190 cm and 140 cm).

This study is the first in-depth investigations of the effect of 3D TVs to eye movement and motor performance. The parameters could be beneficial for developers [35,36] and virtual reality researchers [59–63] to enhance the human performance of 3D TVs.

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References

1. Minoli, D. *3D Television (3DTV) Technology, Systems, and Deployment: Rolling out the Infrastructure for Next-Generation Entertainment*; CRC Press: Boca Raton, FL, USA, 2010.
2. Bowman, D.; Kruijff, E.; LaViola, J.J., Jr.; Poupyrev, I.P. *3D User Interfaces: Theory and Practice, CourseSmart eTextbook*; Addison-Wesley: Boston, MA, USA, 2004.
3. Fernando, A.; Worrall, S.T.; Ekmekciolu, E. *3DTV: Processing and Transmission of 3D Video Signals*; John Wiley & Sons: Hoboken, NJ, USA, 2013.
4. Zhou, J.; Wang, L.; Yin, H.; Bovik, A.C. Eye movements and visual discomfort when viewing stereoscopic 3D content. *Digit. Signal Process.* **2019**, *91*, 41–53. [CrossRef]
5. Teather, R.J.; Stuerzlinger, W. Pointing at 3d target projections with one-eyed and stereo cursors. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Paris, France, 27 April–2 May 2013; pp. 159–168.
6. Machuca, M.D.B.; Stuerzlinger, W. Do stereo display deficiencies affect 3D pointing? In Proceedings of the Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems, Montreal, QC, Canada, 21–26 April 2018; pp. 1–6.
7. Lin, C.J.; Prasetyo, Y.T.; Widyaningrum, R. Eye movement measures for predicting eye gaze accuracy and symptoms in 2D and 3D displays. *Displays* **2019**, *60*, 1–8. [CrossRef]
8. Lin, C.J.; Widyaningrum, R. Eye pointing in stereoscopic displays. *J. Eye Mov. Res.* **2016**, *9*. [CrossRef]
9. Fuchs, P. *Virtual Reality Headsets—A Theoretical and Pragmatic Approach*; CRC Press: Boca Raton, FL, USA, 2017.
10. Sharples, S.; Cobb, S.; Moody, A.; Wilson, J.R. Virtual reality induced symptoms and effects (VRISE): Comparison of head mounted display (HMD), desktop and projection display systems. *Displays* **2008**, *29*, 58–69. [CrossRef]
11. Holmqvist, K.; Nyström, M.; Andersson, R.; Dewhurst, R.; Jarodzka, H.; Van de Weijer, J. *Eye Tracking: A Comprehensive Guide to Methods and Measures*; OUP Oxford: Singapore, 2011.
12. Artal, P. *Handbook of Visual Optics*; CRC Press, Taylor & Francis Group: Boca Raton, FL, USA, 2017.
13. Čegovnik, T.; Stojmenova, K.; Jakus, G.; Sodnik, J. An analysis of the suitability of a low-cost eye tracker for assessing the cognitive load of drivers. *Appl. Ergon.* **2018**, *68*, 1–11. [CrossRef] [PubMed]
14. Bækgaard, P.; Jalaliniya, S.; Hansen, J.P. Pupillary measurement during an assembly task. *Appl. Ergon.* **2019**, *75*, 99–107. [CrossRef] [PubMed]
15. Goldberg, J.H. Measuring software screen complexity: Relating eye tracking, emotional valence, and subjective ratings. *Int. J. Hum.-Comput. Interact.* **2014**, *30*, 518–532. [CrossRef]
16. Lin, C.J.; Chang, C.-C.; Lee, Y.-H. Evaluating camouflage design using eye movement data. *Appl. Ergon.* **2014**, *45*, 714–723. [CrossRef]
17. Read, J.C.; Godfrey, A.; Bohr, I.; Simonotto, J.; Galna, B.; Smulders, T.V. Viewing 3D TV over two months produces no discernible effects on balance, coordination or eyesight. *Ergonomics* **2016**, *59*, 1073–1088. [CrossRef]
18. Read, J.C. Viewer experience with stereoscopic 3D television in the home. *Displays* **2014**, *35*, 252–260. [CrossRef]
19. Lambooij, M.; IJsselsteijn, W.A.; Heynderickx, I. Visual discomfort of 3D TV: Assessment methods and modeling. *Displays* **2011**, *32*, 209–218. [CrossRef]
20. Lee, S.-I.; Jung, Y.J.; Sohn, H.; Speranza, F.; Ro, Y.M. Effect of stimulus width on the perceived visual discomfort in viewing stereoscopic 3-D-TV. *IEEE Trans. Broadcast.* **2013**, *59*, 580–590. [CrossRef]
21. Chang, J.; Jung, K.; Kim, W.; Moon, S.K.; Freivalds, A.; Simpson, T.W.; Baik, S.P. Effects of weight balance on a 3D TV shutter type glasses: Subjective discomfort and physical contact load on the nose. *Int. J. Ind. Ergon.* **2014**, *44*, 801–809. [CrossRef]

22. Chang, J.; Moon, S.K.; Jung, K.; Kim, W.; Parkinson, M.; Freivalds, A.; Simpson, T.W.; Baik, S.P. Glasses-type wearable computer displays: Usability considerations examined with a 3D glasses case study. *Ergonomics* **2018**, *61*, 670–681. [CrossRef]
23. Zang, B.; Zhou, J.; Xiong, J. What is the 3D comfort difference experienced via VR glasses and 3D-TV. In *Digital TV and Multimedia Communication, Proceedings of the International Forum on Digital TV and Wireless Multimedia Communications, Shanghai, China, 20–21 September 2018*; Springer: Singapore, 2019; pp. 261–272.
24. Urvoy, M.; Barkowsky, M.; Le Callet, P. How visual fatigue and discomfort impact 3D-TV quality of experience: A comprehensive review of technological, psychophysical, and psychological factors. *Ann. Telecommun.* **2013**, *68*, 641–655. [CrossRef]
25. Chen, C.; Wang, J.; Li, K.; Liu, Y.; Chen, X. Visual fatigue caused by watching 3DTV: An fmri study. *BioMed. Eng. OnLine* **2015**, *14*, S12. [CrossRef]
26. Manshouri, N.; Maleki, M.; Kayikcioglu, T. An EEG-based stereoscopic research of the PSD differences in pre and post 2D&3D movies watching. *Biomed. Signal Process. Control* **2020**, *55*, 101642.
27. Chen, C.; Li, K.; Wu, Q.; Wang, H.; Qian, Z.; Sudlow, G. EEG-based detection and evaluation of fatigue caused by watching 3DTV. *Displays* **2013**, *34*, 81–88. [CrossRef]
28. Lin, C.J.; Widyaningrum, R. The effect of parallax on eye fixation parameter in projection-based stereoscopic displays. *Appl. Ergon.* **2018**, *69*, 10–16. [CrossRef]
29. Lin, C.J.; Prasetyo, Y.T.; Widyaningrum, R. Eye movement parameters for performance evaluation in projection-based stereoscopic display. *J. Eye Mov. Res.* **2018**, *11*. [CrossRef] [PubMed]
30. Prasetyo, Y.T.; Widyaningrum, R.; Lin, C.J. Eye gaze accuracy in the projection-based stereoscopic display as a function of number of fixation, eye movement time, and parallax. In Proceedings of the 2019 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Macao, China, 15–18 December 2019; pp. 54–58.
31. Prasetyo, Y.T.; Widyaningrum, R. Error rate as mediators of the relationships among 2D/3D TV environment, eye gaze accuracy, and symptoms. In Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021), online, 13–18 June 2021; pp. 756–761.
32. Prasetyo, Y.T.; Widyaningrum, R. Eye-hand movement in 3D displays: A structural equation modeling approach. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1072*, 012059. [CrossRef]
33. Prasetyo, Y.T.; Widyaningrum, R. Eye ballistic phase time and eye correction phase time as mediators of the relationships among 2D/3D TV environment, eye gaze accuracy, and symptoms. In *Convergence of Ergonomics and Design*; Advances in Intelligent Systems and Computing; Springer: Cham, Switzerland, 2021; pp. 399–408.
34. Lin, C.J.; Ho, S.-H.; Chen, Y.-J. An investigation of pointing postures in a 3D stereoscopic environment. *Appl. Ergon.* **2015**, *48*, 154–163. [CrossRef]
35. Salvucci, D.D.; Goldberg, J.H. Identifying fixations and saccades in eye-tracking protocols. In Proceedings of the 2000 Symposium on Eye Tracking Research & Applications, Palm Beach Gardens, FL, USA, 6–8 November 2000; pp. 71–78.
36. Frick, A.; Koch, R. LDV generation from multi-view hybrid image and depth video. In *3D-TV System with Depth-Image-Based Rendering*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 191–220.
37. Park, Y.-G.; Jung, H.-C.; Park, M.-K.; Kang, T.-Y.; Kim, B.-M.; Kim, H.-J. Method for Providing a User Interface Using Motion and Device Adopting the Method. U.S. Patent US20120151415A1, 24 August 2012.
38. MacKenzie, I.S. Fitts' law as a research and design tool in human-computer interaction. *Hum.-Comput. Interact.* **1992**, *7*, 91–139. [CrossRef]
39. *Guide Méthodologique pour le Dépistage Visuel (Test Snellen): Programme Santé des Jeunes d'Age Scolaire*; Centre Hospitalier Maisonneuve-Rosemont: Montréal, QC, Canada, 1984.
40. Neggers, S.F.; Bekkering, H. Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal. *J. Neurophysiol.* **2001**, *86*, 961–970. [CrossRef] [PubMed]
41. Bobick, J.; Balaban, N. *The Handy Anatomy Answer Book*; Visible Ink Press: Canton, MI, USA, 2008.
42. Vertegaal, R. A Fitts Law comparison of eye tracking and manual input in the selection of visual targets. In Proceedings of the 10th International Conference on Multimodal Interfaces, Chania, Greece, 20–22 October 2008; pp. 241–248.
43. Watt, S.J.; Akeley, K.; Ernst, M.O.; Banks, M.S. Focus cues affect perceived depth. *J. Vis.* **2005**, *5*, 7. [CrossRef]
44. Hoffman, D.M.; Girshick, A.R.; Akeley, K.; Banks, M.S. Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. *J. Vis.* **2008**, *8*, 33. [CrossRef] [PubMed]
45. Deering, M. High resolution virtual reality. In Proceedings of the 19th Annual Conference on Computer Graphics and Interactive Techniques, Chicago, IL, USA, 26–31 July 1992; pp. 195–202.
46. Liu, L.; van Liere, R.; Nieuwenhuizen, C.; Martens, J.-B. Comparing aimed movements in the real world and in virtual reality. In Proceedings of the 2009 IEEE Virtual Reality Conference, Lafayette, LA, USA, 14–18 March 2009; pp. 219–222.
47. Woodworth, R. *The Accuracy of Voluntary Movement Columbia University Contributions to Philosophy, Psychology and Education*; Columbia University: New York, NY, USA, 1899.
48. Caudek, C.; Proffitt, D.R. Depth perception in motion parallax and stereokinesis. *J. Exp. Psychol. Hum. Percept. Perform.* **1993**, *19*, 32. [CrossRef]
49. Domini, F.; Caudek, C. Perceiving surface slant from deformation of optic flow. *J. Exp. Psychol. Hum. Percept. Perform.* **1999**, *25*, 426. [CrossRef] [PubMed]

50. Loomis, J.; Eby, D. Relative motion parallax and the perception of structure from motio. In Proceedings of the Workshop on Visual Motion, Irvine, CA, USA, 20–22 March 1989; pp. 204–211.
51. Todd, J.T.; Bressan, P. The perception of 3-dimensional affine structure from minimal apparent motion sequences. *Percept. Psychophys.* **1990**, *48*, 419–430. [CrossRef]
52. Drury, C.G. Application of Fitts' law to foot-pedal design. *Hum. Factors* **1975**, *17*, 368–373. [CrossRef]
53. Fitts, P.M.; Peterson, J.R. Information capacity of discrete motor responses. *J. Exp. Psychol.* **1964**, *67*, 103. [CrossRef]
54. Kerr, B.A.; Langolf, G.D. Speed of aiming movements. *Q. J. Exp. Psychol.* **1977**, *29*, 475–481. [CrossRef]
55. Knight, A.; Dagnall, P. Precision in movements. *Ergonomics* **1967**, *10*, 321–330. [CrossRef]
56. Kvålseth, T.O. An alternative to Fitts' law. *Bull. Psychon. Soc.* **1980**, *16*, 371–373. [CrossRef]
57. Wade, M.G.; Newell, K.M.; Wallace, S.A. Decision time and movement time as a function of response complexity in retarded persons. *Am. J. Ment. Defic.* **1978**, *83*, 135–144. [PubMed]
58. Card, S.K.; English, W.K.; Burr, B.J. Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. *Ergonomics* **1978**, *21*, 601–613. [CrossRef]
59. Long, Z.; Liu, L.; Yuan, X.; Zheng, Y.; Niu, Y.; Yao, L. Assessment of 3D visual discomfort based on dynamic functional connectivity analysis with HMM in EEG. *Brain Sci.* **2022**, *12*, 937. [CrossRef]
60. Lin, P.-H.; Jin, Y.-M. Applying fuzzy theory in selecting the image quality factors of 3D televisions. *Int. J. Ind. Ergon.* **2019**, *74*, 102841. [CrossRef]
61. Park, S.; Kyung, G.; Yi, J.; Choi, D.; Lee, S. Curved tvs improved watching experience when display curvature radii approached viewing distances: Effects of display curvature radius, viewing distance, and lateral viewing position on TV watching experience. *PLoS ONE* **2020**, *15*, e0228437. [CrossRef] [PubMed]
62. Wahl, S.; Dragneva, D.; Rifai, K. Digitalization versus immersion: Performance and subjective evaluation of 3D perception with emulated accommodation and parallax in digital microsurgery. *J. Biomed. Opt.* **2019**, *24*, 106501. [CrossRef]
63. Yu, M.; Li, Y.; Tian, F. Responses of functional brain networks while watching 2D and 3D videos: An EEG study. *Biomed. Signal Process. Control* **2021**, *68*, 102613. [CrossRef]