An Assessment of Human Depth Understanding in Handheld Light-Field Displays

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***Abstract*—Light-field displays (LFDs) allow users to view stereoscopic images without the need for a headset, providing a novel 3-Dimensional (3D) experience. This study aims to expand upon the preliminary experiment, in which we evaluated the benefits of stereoscopic cues in human visual understanding through users performing 3D interactions on a multi-view, LFD display. Our task scenario involves user tests for 3D alignment accuracy and a questionnaire about the experience during the test. For each task, using the LFD "Lume Pad" developed by Leia Inc., 3D contents are presented with stereoscopic cues and without. Results from subjects showed that task alignment could be achieved with greater accuracy when stereo cues were available than when there were not. The questionnaire showed that depth perception appeared to be easier to comprehend with stereoscopic cues.**

Keywords-component Light-Field Display; 3D human perception; motion-parallax; stereoscopic vision; head tracking.

I. INTRODUCTION

Two-Dimensional (2D) screens have almost limitless possibilities. These displays can show locations that the user has never seen, visualize data of almost any form, and allows professionals to interact with information in ways that are difficult within a physical medium. Even with all these possibilities, the 2D screen is not perfect. This style screen cannot show true depth, as it is a flat object and does not have any depth to it. This paper is an extension of our previous work, evaluating the benefits of depth comprehension of an LFD over a standard flat screen [1].

The human eye does not interact with a screen in the same way as it does with the real 3D world [2], especially in terms of seeing depth. To aid in recreating depth, there are many tools that can be used to simulate depth cues. There are nine widely agreed-upon sources of information that the human brain uses for the purpose of perceiving depth. They are as follows, binocular disparity, convergence, occlusion, relative size, height in the visual field, relative density, aerial perspective, accommodation, and motion parallax [3]. To a greater or lesser extent, these are the primary tools used in conveying the illusion of depth within a 2D screen, and it is the manipulation of these sources that forms the basis of 3D displays. By putting more focus on one source than others, many different types of 3D displays can be created, each being tailored to suit different tasks.

For most of the populace, VR represents a VR headset, or Head Mounted Display (HMD) as these have had the most exposure in popular culture. The popularity of products such as the HTC VIVE and the Oculus sold by Meta are best known for their entertainment uses but are becoming more well known for their benefits to training, such as cancer patient care [4], as well as in scientific research. The basis of VR HMDs is to use two small, high-resolution displays, placed close to the wearer's eyes. Each display is positioned so that only one eye can see each screen, thus using binocular disparity to create a stereoscopic experience. Each screen displays a slightly different view of the same scene, allowing the user's brain to put them together to create a 3D image. This is to simulate how the human eyes naturally work in the real world where human eyes are slightly split apart, giving us two slightly different views.

Hand-held displays are not usually considered to be a type of 3D display, but they are also capable of displaying believable 3D images. These displays are largely composed of devices not specifically designed for this purpose such as smartphones and tablets, though there are some that are specifically designed to be used for 3D content such as the RED Hydrogen One smartphone and the Nintendo 3DS. Many hand-held displays use apps and programs, such as Pokémon Go or IKEA Place, that use the device's inbuilt camera to give the appearance of projecting objects into the real world via the device's screen. This style of software displays what the camera sees and adds digital objects to the scene to show the user a believable 3D scene. In so doing, this type of 3D display relies largely on height in the visual field, comparing the height of the digital objects to the size of known physical objects in the scene, for the user to believe that what they are looking at is real.

Another device that is designed to create stereoscopic images in a different way is known as an LFD. LFDs use curved lenses, such as lenticular lenses, to redirect the light coming out of the screen of the display [5]. By doing this, the LFD can split the display so that it gives a different view to each eye. In this way, an LFD works similarly to an HMD, though the LFD performs this job without the need for a headset. This also allows for more than one user to be able to see the 3D effect from the same display.

The purpose of this study is to improve on our preliminary findings and to show that adding stereoscopy to a tablet display increases a user's understanding of what it is that they are seeing. To this end, the new experiment has more easily understood user controls, so the experiment emphasizes visual understanding and not mastery of the controls. The experiment also has less visual stimulation, to help the subjects focus on the important details of the experiment.

The remainder of the paper is structured as follows. In Section II, we present our experiment's methodology for evaluating the subject's accuracy with and without stereoscopy. Section III covers the details of the hardware and software used in the experiment. Our preliminary experiment is discussed in Section IV, both our findings and what we felt needed to be improved for a follow-up experiment. Section V details the experiment as well as the results and questionnaire. In Section VI we discuss our findings and the implications. Finally, we finish our work in Section VII, with our conclusion and discuss future work.

II. Methods

The focus of this study was to measure a subject's understanding of a 3D scene displayed on a 2D screen, given different visual cues. To measure accuracy, subjects were asked to aim an arrow at a target, using the visual cues available to them to attempt to hit as close to the center of the target as they could. This test was repeated four times with some changes to assess the subject's understanding of the scene.

A. Visual Cues

The primary visual cues that are observed in this test are occlusion, motion parallax, and stereoscopy. Occlusion happens when an object blocks the line of sight to another object. This technique has been used for centuries as a method of showing depth in many different forms of illustrations.

Humans see objects closer to them as moving faster than objects that are further away. This is more prevalent in a vehicle moving at speed and is known as motion parallax. Both visual cues are prevalent throughout the entire experiment.

B. Accuracy Test

To assess the subject's understanding of the simulated depth within the screen, a 3D scene was created to interact with. This scene includes an arrow, target, obstacles, and minute details to enhance the visual cues within the scene.

The target, as seen in Figure 1, is at a set *y* position, 7 meters, and is offset by a distance in the *x* and *z* directions. This distance changes for each test, as seen in Figure 2, altering the ideal arrow angle and camera position for each test.

To obscure the subject's view and encourage them to interact with the scene, obstacles are added to the scene. A rock is placed directly behind the arrow, stopping subjects from simply positioning the camera behind the arrow and lining up their aim this way. By doing this, the subject would not require the visual cues we are evaluating. There are also four trees that are placed to further complicate the scene and encourage more interaction. These trees change their location after each test much like the target.

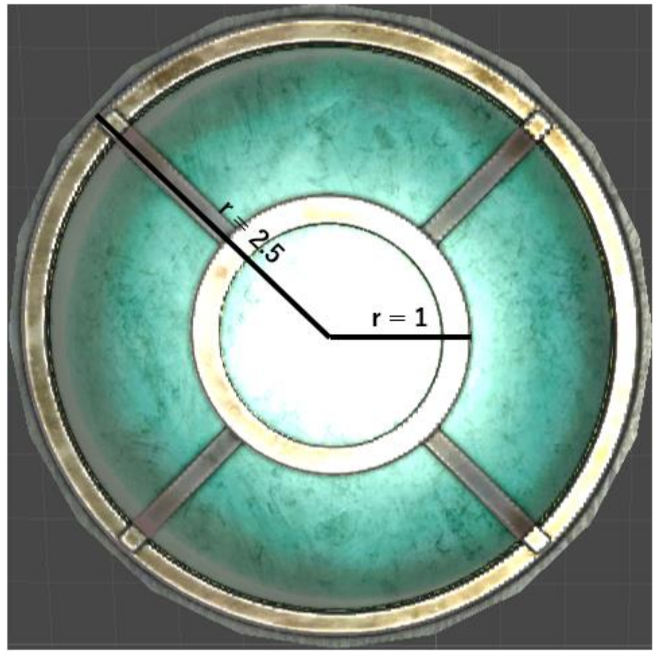


Figure 1. Target.

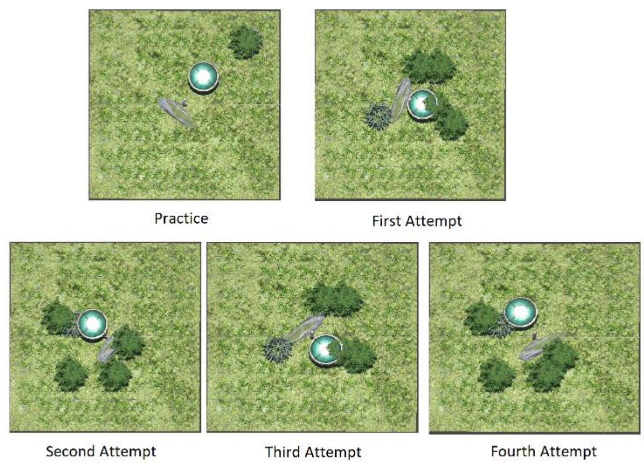


Figure 2. Top-down view of Accuracy Test.

C. Accuracy Measurement

To measure the subject's understanding of the scene, the distance from the arrow to the center of the target is measured. Euclidean distance is used for this measurement. A lower distance is desirable as it shows the subject was able to aim the arrow close to the center of the target.

$$Distance = \sqrt{(x_1 - x_2)^2 + (z_1 - z_2)^2} \quad (1)$$

In this equation, x_1 and z_1 correspond to the position of the target while x_2 and z_2 to the final location of the arrow. The unit of measure for the experiment is Unity units, which are equivalent to meters (m). A score of less than 1 was considered a good score, as it hit within the center ring of the target, while a score between 1 and 2.5 was considered an acceptable score, as it hit the outer ring. A score of above 2.5 missed the target and was considered a poor score.

D. Head Tracking

Another key to this research was the decision to perform head tracking. With an LFD, head movements change the view that the user is seeing, therefore moving around gives different viewing angles into the same scene. We believe that subjects will benefit from seeing these different views. Head movement is not required for the test though. A user can perform the entire test without moving their head enough to shift which view they are seeing.

Two VIVE trackers were used to monitor the position of the subject's head in relation to the position of the tablet. One tracker was placed on a stand so that it is positioned just below the tablet. The tracker sits 8 cm above the table, with the bottom of the tablet being 13 cm above the table and the top of the tablet being 30 cm above the table. The second tracker was attached to the user's head via a head strap. This allowed for the user's head position and rotation to be monitored both on their own, as well as in relation to the tablet, as seen in Figure 3.

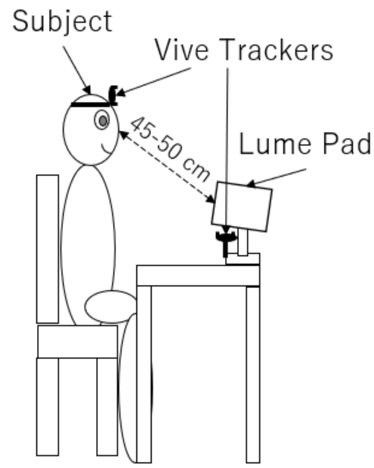


Figure 3. Experiment Setup.

Figure 4. Subject Participating in Experiment.

E. Experimental Procedure

The procedure for the experiment was as follows. Firstly, the subject was sat at the table, put on the head tracker, and told what was expected of them as well as given a description and short demonstration of how the controller worked. Then they were given a practice scene and told to spend as much time as they needed to feel comfortable with how to control the arrow and move the camera but were instructed to not press the X button. Once they felt comfortable, they were instructed to press the X button and the test began. The subject performed the first four tests, then the experiment was reset, and the Light-field effect was either turned on or off, depending on which group the subject was in. After this, they were asked to do another four tests. Finally, they filled out a short questionnaire.

Subjects sat 45-55 centimeters from the Lume Pad as seen in Figures 3 and 4. This is the distance that Leia Inc states is the best viewing distance for observing the stereoscopic visual cues that the Lume Pad produces. The tablet itself was positioned on a stand that was adjusted for each user to give them the best viewing angle. The subject's horizontal position was not considered as the subjects were free to move to observe the different views displayed by the LFD.

Subjects were separated into two groups. Group one performed the practice as well as the first four tests without the Light-field effect turned on, then the Light-field effect was turned on and they performed another four tests. Group two performed the practice and first four tests with the Light-field effect turned on, then it was turned off for the second four tests.

III. Hardware and Software used in Experiment

A. Lume Pad

The following research was performed using a Lume Pad, an LFD tablet produced by Leia Inc. As discussed above, this allows users to see the illusion of depth inside a 2D screen by creating stereopsis. The tablet boasts a 10.1-inch screen with a resolution of 2560x1600 pixels.

To create the light field effect, the tablet displays four views at the same time and uses lenticular lenses to allow the user to see two of these images at a time. If the user moves to the sides they will see two different images, thus creating a different view. In this way, the Lume Pad creates three views that can be viewed by changing the user's viewing angle.

To generate the different views, the Lume Pad stores four images internally as a single image file broken into a 2x2 grid. Due to needing to put four images into one screen, each image can only make use of one-quarter of the total resolution, so each view has a resolution of 640x400 pixels [6].

One way to measure how much detail a screen can show is through pixel density. This is calculated as follows,

$$PPI = \frac{Diagonal\ in\ Pixels}{Diagonal\ in\ Inches} \quad (2)$$

$$Diagonal\ in\ Pixels = \sqrt{Width^2 + Height^2} \quad (3)$$

The width and height pertain to the dimensions of the tablet. In this case, the Lume Pad has a width of 2560 pixels and a height of 1600 pixels. Given this, the pixel density of each image within an LFD image on the Lume Pad, is 75 pixels per inch (ppi) which is small compared to the potential of the tablet without the Light-field turned on, which has a pixel density of 290 ppi. This is not a favorable comparison as the LFD uses only 25.9% of the pixels per image for each of its images, though this is to be expected and is a misnomer. For a more realistic comparison, the LFD can be compared to a standard computer monitor. A popular computer screen size is 24 inches with a resolution of 1920x1080 pixels, giving this screen a pixel density of 92 ppi. This is a much more favorable comparison for the Lume Pad with the LFD turned on, as it has 81.5% of the pixel density of a standard computer screen.

The Lume Pad uses a few techniques to make the display appear to have a clear picture even with its slightly low resolution. These include having a smaller screen size compared to a desktop or laptop computer as well as the orientation of the lenticular lenses. These lenses are not aligned vertically but are instead slanted slightly. This allows for smoother transitions between views as well as allowing for vertical changes of view and not just horizontal changes of view. It has also been shown as an effective way to blend views together, making the user believe they are able to see more views than are being displayed [7].

B. *Sony Dual Sense Controller*

A Sony Dual Sense controller was chosen as the input tool for this experiment for a few reasons. Firstly, it is Bluetooth compatible, so it can easily connect to the Lume Pad. Secondly, it is a familiar controller in both shape and layout to many people as it follows a similar layout to popular home gaming systems.

The directional pad (d-pad) on the left side of the controller, is used to control the arrow, allowing the user to aim it to the facing that the subject believes will hit the center of the target to the best of their ability. On the right side of the controller, the southern button, the X, on the controller, launches the arrow. The western button, the Square button, resets the test and the northern button, the Triangle button, turns the LFD effect on and off.

The left stick controls the scene rotation, but it only rotates the scene camera around the center point on the horizontal axis. There is no way to move the camera on the vertical axis. This decision was made because the Lume Pad works best with multiple horizontal views and not multiple vertical views. The right shoulder button zooms the camera in while the left zooms the camera out. The full controller layout can be seen in Figure 5.

C. *Unity*

Our experiment was designed using the Leia Unity Software Development Kit (SDK) [8]. This SDK allows for the utilization of the Lume Pad's features, such as the special Leia camera, as well as having the ability to turn the LFD on and off within the test. The Leia camera is four cameras, aligned in parallel with each other. Aligning the cameras in parallel is important to avoid the keystone distortion and depth plane curvature, as seen in Figure 6, that can occur with a toed-in camera [9]. This distortion is not as visible at close range but at a longer range the image warps in a way that does not align with how human eyes naturally see the world.

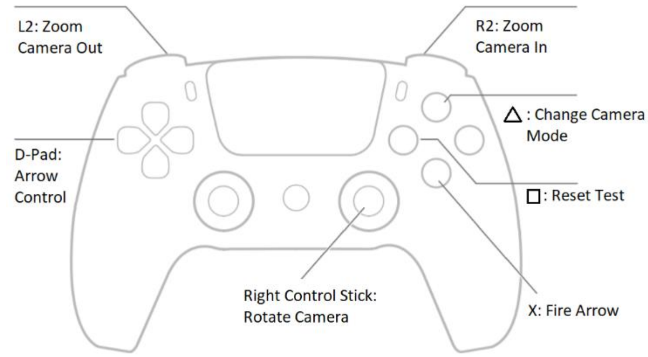
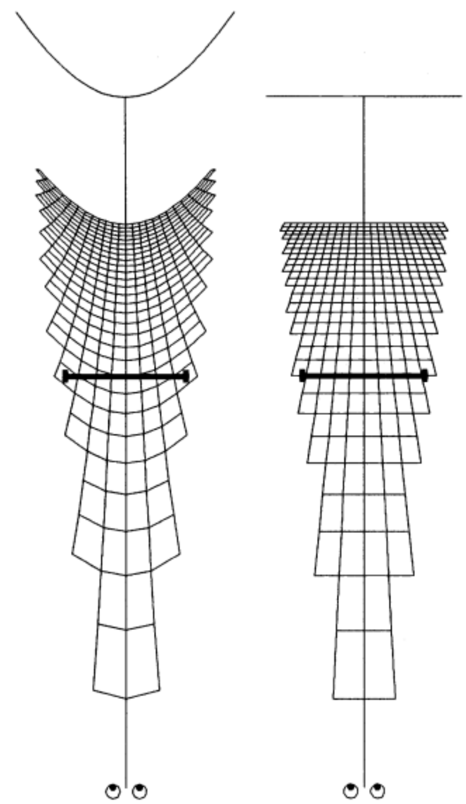


Figure 5. Sony Dual Sense Controller - Layout.



(a) Keystone Distortion (b) No Distortion

Figure 6. Keystone Distortion.

IV. PRELIMINARY EXPERIMENT

In the preliminary experiment, 12 subjects (3 females and 9 males) were asked to fire an arrow at a target. Subjects were split into two groups, with group one testing with the Light-field turned off first and then turned on, while group two did the same but in reverse. In that experiment, the subjects performed three tests, with the target being placed further away from the arrow with each test. Then the LFD was switched off or on, depending on the subject's group, and three more attempts were performed. The data collected was the distance from the center of the target as well as the time it took for each attempt.

A. Results

The results can be viewed in Table 1. The scores are the median value of all attempts that each subject performed. The overall mean of the tests with the Light-field turned on, 1.881, was lower than when it was turned off, 2.264. This shows that overall, the subjects were on average more accurate with the Light-field turned on. Furthermore, we can see from this data that group two was more accurate than group one on average. Within the groups, another interesting point can be observed. Group one was more accurate on average with the Light-field effect turned on than with it off, with scores of 2.119 and 2.666, respectively. Group two follows the same pattern, with scores of 1.644 with the Light-field turned on and 1.863 with it turned off.

While it is tempting to state that this proves our hypothesis that stereoscopy increases the user's understanding and thus their accuracy, this data does not allow us to state this. A two-way ANOVA to analyze the effect of test order and the Light-field effect on subject accuracy was performed. Simple main effects analysis showed that test order did not have a statistically significant effect on subject accuracy (p = 0.1118). Similarly, the analysis showed that the Light-field effect did not have a statistically significant effect on subject accuracy either (p = 0.3305).

The two-way ANOVA revealed that there was not a statistically significant interaction between the effects of test order and the Light-field effect ($F(1, 20) = 0.1829$, p = 0.6735).

These results show that the preliminary experiment strengthens the hypothesis that the stereo effect of the LFD was beneficial to the subjects, but the results were not conclusive. We observed that the first group did get more accurate when stereoscopy was added and that the second group was more accurate while using stereoscopy than without. The results of the ANOVA were a large problem though, as it is not clear that it is mainly the Light-field effect that is affecting subject accuracy.

B. Improvements for the Main Experiment

The most critical issue that needed addressing in further experiments was the precision of the controls. Some of the subjects stated that the controls were too imprecise to feel confident in their accuracy with these tests. Trying to make minute changes to the aim of the arrow proved difficult to achieve using the dual sense controller's control stick. For some subjects, this was partially due to unfamiliarity with the controller. A control stick is intuitive to those that often play video games, but confusing to those who do not.

Another reason is due to how hard it is to control an object when it has free movement in three dimensions. While some users were able to control the arrow without much effort, feeling that they understood where the arrow was pointing at all times, others constantly overcorrected their aim and had to try to bring it back to where they wanted the arrow pointing. This tested some subjects' patience, and a few seemed to decide they were close enough instead of trying to be as precise as possible. By making the controls more precise and easier to operate, we believe that users would be more confident in their accuracy with the test, and as such it would be clearer how much of a significant role the Light-field played in subject accuracy.

Based on feedback and further research, changes were proposed to the scene itself. Moving the target closer to the arrow is one such change. In the preliminary experiment, the later tests placed the target at a distance that made it difficult to understand where it was on the small screen.

Some scenery was removed as well, being one of the trees and a portion of the grass. The tree was deemed to be unnecessary as there were already enough obstacles blocking sight lines. The grass was there to give the user more visual cues to perceive motion parallax, but the amount of detail that the display needed to render was affecting its performance and we also worried that there were perhaps too many cues for the user [10].

In our previous paper, we discussed performing eye tracking as a possible addition to future research, but it was decided that head tracking would give more significant data than eye tracking. The reasoning behind this was that eye tracking would show eye vergence [11], giving a better understanding of how subjects' brains perceive the scene displayed on the LFD, while head tracking indicates the user's interaction with the device. Head tracking was chosen over eye tracking because an LFD is a flat screen, so eye vergence will not be the same as if the scene was in real 3D and would likely behave as they were interacting with a standard 2D screen. Thus, head tracking was deemed to be more noteworthy.

TABLE 1. PRELIMINARY EXPERIMENT RESULTS

		Subject	Display: Without LFD	Display: With LFD	Mean	St. Dev
Group	I	1	2.234	2.175	2.392	1.2167
		3	2.054	1.673		
		5	2.408	1.993		
		7	2.490	1.907		
		9	5.422	4.058		
		11	1.387	0.905		
	II	2	1.363	1.859	1.753	0.4729
		4	1.580	0.861		
		6	1.927	1.946		
		8	2.842	2.083		
		10	1.731	1.433		
		12	1.733	1.681		
		Mean	2.264	1.881		
		St.Dev	1.0935	0.8069		

V. Experiment and Results

For the experiment, there were 8 subjects (one female and seven males). They ranged in age from 22 to 27 with an average age of 25. All had either normal or corrected-to-normal vision. The experiment was carried out over two days, with subjects asked not to discuss the test with other subjects. Each subject was assigned a number, with odd-numbered subjects placed in group one while even-numbered subjects were placed in group two.

Table 2. Main Experiment Results

		Subject	Display: Without LFD	Display: With LFD	Mean	St. Dev
Group	I	1	0.318	0.519	1.229	1.0047
		3	1.321	0.722		
		5	3.454	1.640		
		7	0.641	1.218		
	II	2	1.467	0.742	1.511	0.8159
		4	0.462	0.912		
		6	1.998	1.343		
		8	2.748	2.412		
		Mean	1.551	1.189		
		St.Dev	1.1244	0.6174		

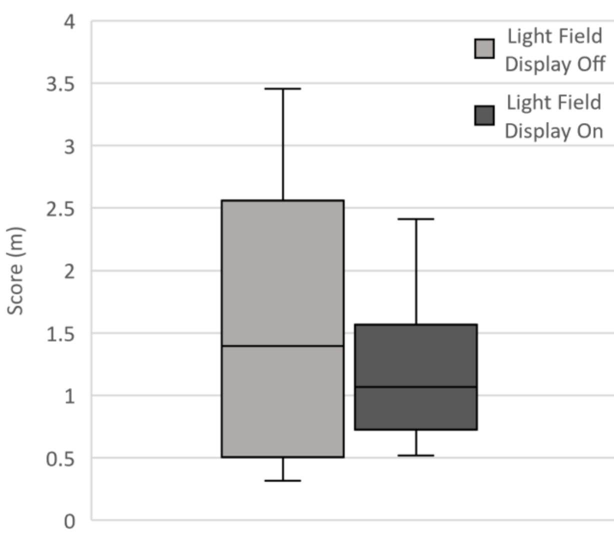


Figure 7. Interquartile Range

A. Scores

Table 2 displays the accuracy results of the experiment. From this table, it can be observed that on average, subjects were more accurate when they had access to stereoscopy, with the LFD effect turned on. On average with the LFD turned on, the average score was 1.189, which would miss the inner circle of the target by 0.189 meters. The low variance, the square of the standard deviation, of 0.381 means that this is a rather reliable estimation. With the LFD turned off, the subjects on average had a score of 1.189, which would hit the outer circle of the target, though with a high variance of 1.264 this number is not as reliable as the results with the LFD on.

Due to the small data set, another way to evaluate this data is by looking at the interquartile range. This is a look at the range of the inner two-quarters of the data. It is useful in small data sets by removing outliers and observing the distance between the data around the mean. When the LFD is turned off the interquartile range is 1.826, while with the LFD turned on the interquartile range is 0.760. Figure 7 visualizes this information.

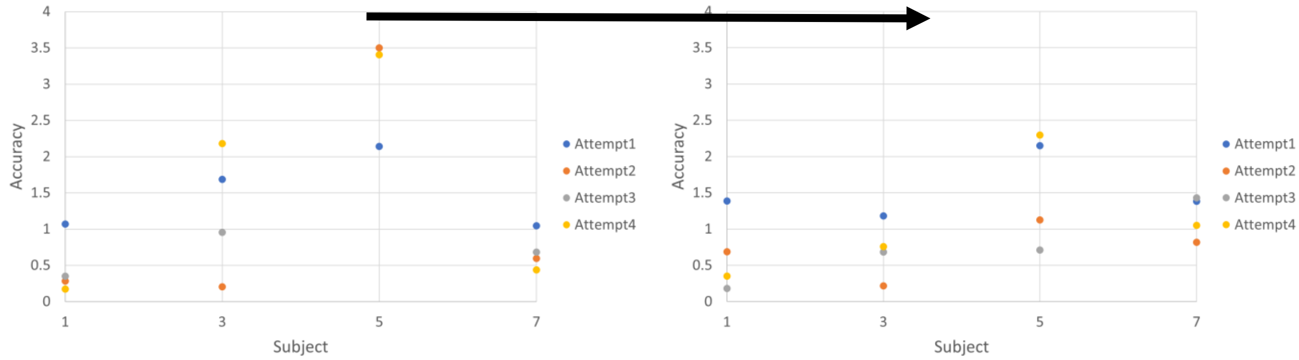
As with the preliminary experiment, a two-way ANOVA was performed to analyze the effect of test order and the Light-field effect on subject accuracy. Simple main effects analysis showed that test order did not have a statistically significant effect on subject accuracy (p = 0.6944). Similarly, the analysis showed that the Light-field effect did not have a statistically significant effect on subject accuracy either (p = 0.4676).

The two-way ANOVA revealed that there was not a statistically significant interaction between the effects of test order and the Light-field effect ($F(1, 12) = 0.0091$, p = 0.9256).

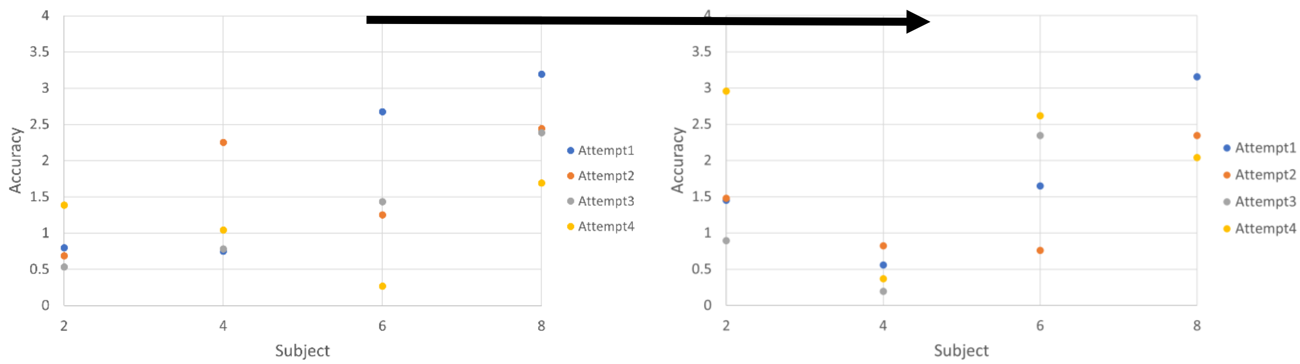
Figure 8 allows for a more visually direct comparison of the individual results of the two groups and the two tests. Within Group 1, shown in Figure 8 (a), subjects 3 and 5 both were more accurate when the Light-field was turned on for the second half of the experiment. Subjects 1 and 7 were less accurate, but both were still very accurate and did not miss the target.

Group 2 is similar, as shown in Figure 8 (b), where subjects 2 and 8 are less accurate when the Light-field is turned off, subject 8's third test is so far off the target it does not appear on the graph. Subject 4 is more accurate when the Light-field it turned off, and subject 6 appears to be the roughly the same over both tests.

Furthermore, it can be seen that the target was missed twice with the Light-field effect turned on but was missed seven times with it turned off. The center ring was hit 14 times in both tests.



(a) Group 1 Accuracies. Light-Field Off, then On



(b) Group 2 Accuracies. Light-Field On, then Off
Figure 8. Accuracy Plot

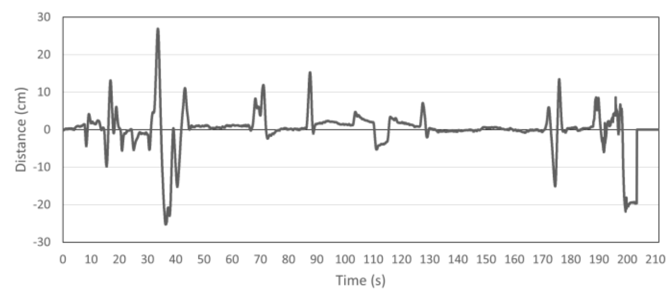
B. *Head Tracking*

The head tracking data can be observed in Figures 9 (a) and (b). As only the horizontal distance changes the view that the subject sees within the LFD, the X value is the only variable that we have recorded in these graphs. Within the graphs, the distance, measured in centimeters, to the left or right of the centerline of the tablet is displayed. The distance traveled to the right is recorded as a positive value while the distance traveled to the left is recorded as a negative value.

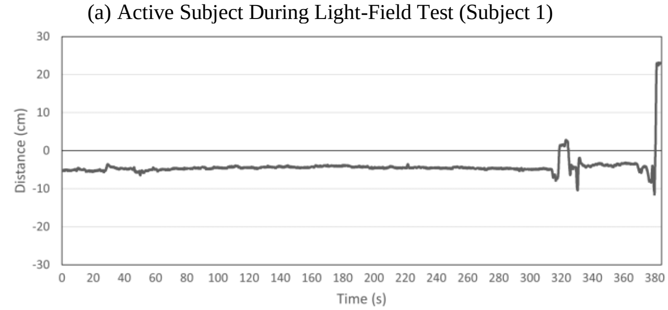
A comparison of subjects 1 and 7 shows the difference in how each interacted with the tablet. Subject 1 scored the best median accuracy over the Light-field tests, with a score of 0.519. They actively moved their head while the Light-field effect was turned on, as seen in Figure 9 (a), moving close to thirty centimeters to either side of the centerline of the tablet at times. In comparison, subject 7, whose data can be seen in Figure 9 (b), tried a small head movement at the beginning and then moved very little until the end of the experiment. They had a median score of 1.218. While head movement may not have been the leading factor for this disparity in the two subject's scores, it could possibly have affected them.

C. *Time Comparison*

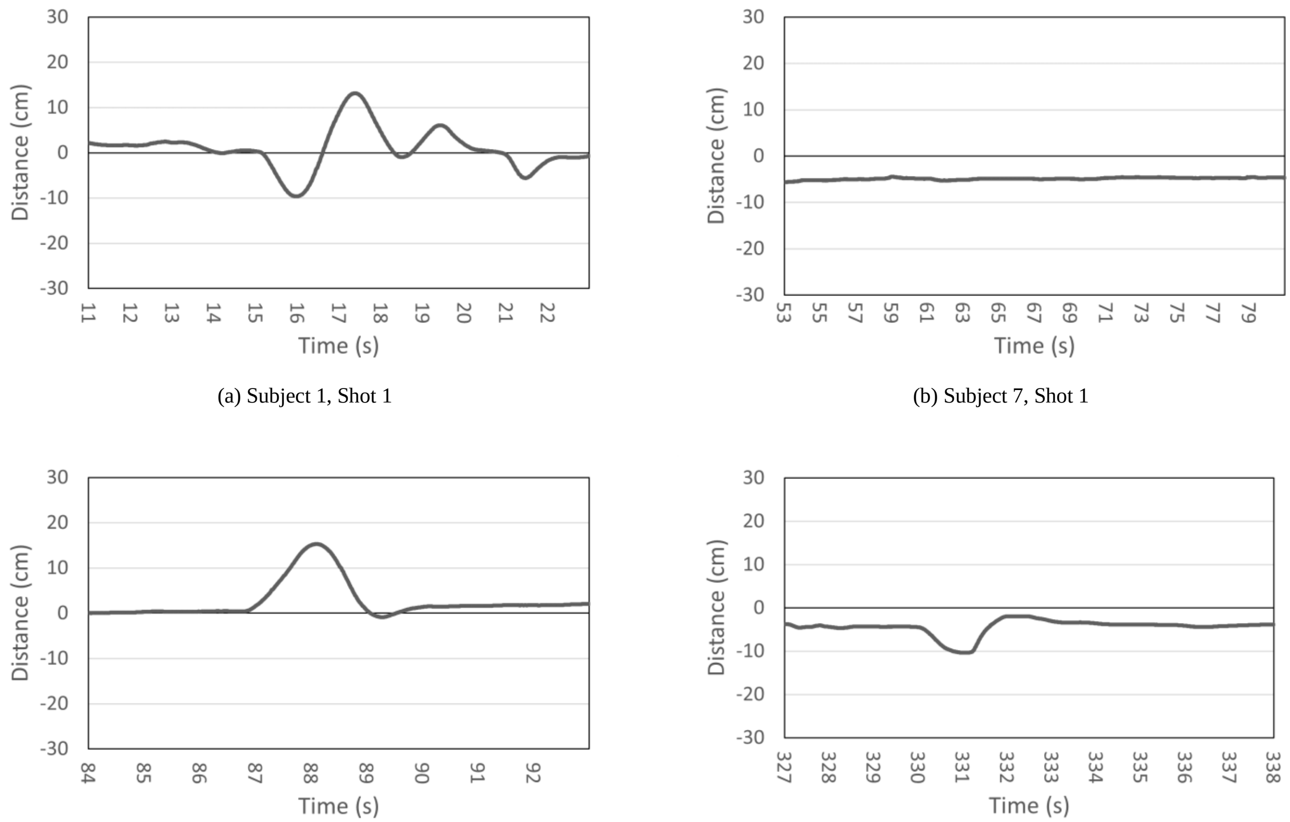
Table 3 shows the median time spent by each subject for each test. Some subjects were quicker while others took more time. A further comparison of subjects 1 and 7, specifically looking at the times in which they were performing the Light-field tests illustrates how much time some subjects felt they needed for each portion of the experiment. Overall, Subject 2 spent around 200 seconds performing this portion of



(a) Active Subject During Light-Field Test (Subject 1)



(b) Inactive Subject During Light-field Test (Subject 7)
Figure 9. Comparison of Active and Inactive Subjects



(a) Subject 1, Shot 1

(b) Subject 7, Shot 1

(c) Subject 1, Shot 4

(d) Subject 7, Shot 4

Figure 10. Head Movement Comparisons.

TABLE 3. TIME COMPARISON

		Subject	Display: Without LFD	Display: With LFD	Mean	St.Dev
Group	I	1	22.91	24.90	41.29	23.870
		3	73.57	56.07		
		5	19.51	12.26		
		7	54.89	66.18		
	II	2	12.26	24.90	30.52	19.858
		4	23.60	29.10		
		6	66.18	56.07		
		8	16.94	15.13		
		Mean	36.23	35.58		
		St.Dev	24.503	20.729		

the experiment while Subject 7 spent around 350 seconds, over two minutes longer. For their first shot, Figure 10 (a), with the Light-field turned on, subject 1 spends a few seconds observing and interacting with the test before moving their head to look at the different views. At this point, they move 10 centimeters to the left, then about 13 to the right. Afterward, they make much less drastic movements as they finish aiming the arrow. The process takes about 12 seconds. By contrast, in the exact same scenario, Figure 10 (b) shows that subject 7 spends the entirety of their first shot focusing on the scene and not utilizing the other views available if they moved their head. Subject 7 took more than double the time that subject 1 took, at 27 seconds. A similar comparison can be made over their last shot. Subject 1 only makes one movement of around 15cm at about halfway through this shot. They take roughly 9 seconds to perform their final test. Subject 7 by contrast makes a similar movement four seconds into their final attempt which lasts 11 seconds. In both cases, subject 1 spends less time, and moves more. One interpretation of this is that subject 7 spent that time making up for not seeing the other views that Subject 1 utilized.

D. *Questionaire*

Subjects were also given a questionnaire to ascertain how well they believed they had understood the experiment. The questions were as follows:

1) *How confident were you that you would hit the center of the target with the LFD turned off?*

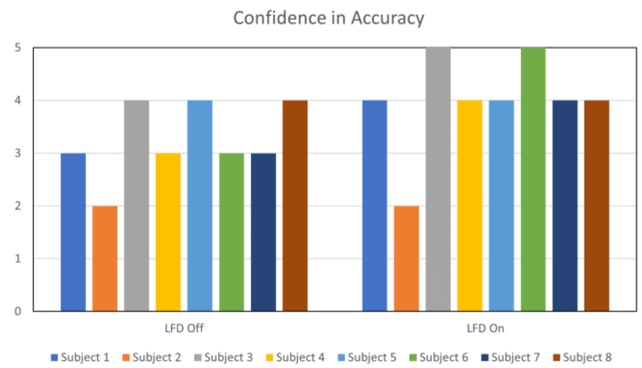


Figure 11. Confidence in Accuracy.

2) *How confident were you that you would hit the center of the target with the LFD turned on?*
3) *Were you more confident with the LFD turned on, off, or neither?*
4) *When the LFD was turned on, did you feel that moving your head to see the other viewing angles helped to improve your accuracy?*
5) *Did you feel dizzy or sick at any time during the test?*

Figure 11 shows the results of the first two questions of the questionnaire. Subjects were asked to rank their confidence on a scale of 1 to 5, where 1 was not confident at all, 3 was somewhat confident, and 5 was extremely confident. Most subjects stated that they felt more confident with the Light-field turned on. Although subjects 2, 5, and 8 ranked their confidence the same over both tests, they stated that they felt they were marginally more confident with the Light-field turned on than with the Light-field effect turned off.

All subjects agreed that they did not feel that moving their head to see other viewing angles helped them. Finally, two subjects felt dizzy when the Light-field effect was turned off, though not so bad that they felt they needed to stop the experiment.

VI. DISCUSSION

Although subjects were encouraged to move their head to see the other views that the LFD generates, every one of them stated that they did not believe that doing this helped with their accuracy. While objects in the foreground and background would move as the view was shifted, the objects near the arrow and the target rarely did. The foreground movement was sometimes slightly helpful, but not enough to make a difference in user confidence.

After further testing, it was concluded that the convergence distance was too short for the different views to have noticeable changes. The convergence distance is the distance from the camera where all camera points converge. One way to think about this is that whatever objects are set at the convergence distance are the focal point. In this test, that was set to be the arrow so that it was always in focus. In the preliminary experiment, the convergence distance was set at 10 meters from the camera, and this led to 2 subjects saying that they felt they could not pull the camera very far from the arrow because then they were unsure of the direction that the arrow was facing. Because of this, both of them took what they believed to be too much time aiming the arrow for each test.

A compromise would be to set the convergence point some distance behind the arrow. This would create more differences in the views. This causes the arrow to be less in focus, making it more difficult to be confident in knowing where the arrow is pointing exactly. With more testing, a good compromise can be achieved.

Another option would be to increase the distance between each camera within the Leia camera. This causes a larger difference between each view from the Lume Pad, and also increases the feeling of stereopsis in the user, as the view given to each eye is spaced further apart. This is also dangerous though as if this is spread too far, it appears unnatural and can cause motion sickness.

VII. CONCLUSION AND FUTURE WORK

In this study, we examined the accuracy of a user's understanding, given some constraints, with a 3D scene on an LFD in an attempt to show that the human brain understands a scene displayed on an LFD better than a standard 2D screen. While the subjects were more accurate with the Light-field turned on, it is not conclusive that the human brain understands simulated distance in the light field display more so than that simulated with a 2D screen. With the two-way ANOVA once again being inconclusive we are not able to say definitively that the reason that the subjects were, on average, more accurate with the Light-field on than with it turned off.

To further this experiment, enhancing the change in views when the subject moves their head is the priority. Creating a stereoscopic viewing experience without the use of a headset is the most well-known feature of an LFD, but the fact that it can be viewed from multiple angles to see different views is a feature that should be further explored. Both changing the convergence distance as well as experimenting with increasing the distance between cameras should be fully explored in further work.

Another feature that goes along with the LFD being able to show multiple views at one time is that it can be used by multiple people at the same time. This concept has been explored on large-scale LFDs, such as the 120-degree viewing angle LFD designed by Liu et al. [12]. This LFD is far more complicated than the Lume Pad, requiring vast amounts of space and hardware to set up. The Lume Pad has a much smaller optimal viewing angle but more than one user can still fit within this space. Finding a way to test how well two subjects can interact with and understand what is being shown to them with one Lume Pad would give us useful information for future work.

An idea that would utilize this concept would be a cube-style display. The pCubee, by Stavness et al. [13] is a multiscreen display comprised of 5 screens arranged in a cube formation, each connected to a control board. By using a head tracker and an accelerometer, the control boards change the view on each screen to create a believable 3d image without using stereopsis. Since the cube reacts to the user's interactions, it feels like the user is looking into the cube and seeing real depth. By using Lume Pads, or a similar device, a similar experience could be created, without the need for the head tracker. Similar to the pCubee, an accelerometer would detect movements and inform the screens to change their views accordingly, while the lenticular lenses would display the extra views required for any head movements that the subject performs. It could also be designed to give multiple viewers the same experience at one time. Instead of directing all of the screens to one viewpoint, multiple viewpoints can be defined and the LFDs can create them at the same time.

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