Do 3D Visual Illusions Work for Immersive Virtual Environments?

Filip Škola
CYENS – Centre of Excellence
Nicosia, Cyprus
f.skola@fqs.cz

Roman Gluszny
Solarwinds
Brno, Czech Republic
roman.gluszny@solarwinds.com

Fotis Liarokapis
CYENS – Centre of Excellence
Nicosia, Cyprus
f.liarokapis@cyens.org.cy

***Abstract*—Visual illusions are fascinating because visual perception misjudges the actual physical properties of an image or a scene. This paper examines the perception of visual illusions in three-dimensional space. Six diverse visual illusions were implemented for both immersive virtual reality and monitor based environments. A user-study with 30 healthy participants took place in laboratory conditions comparing the perceptual effects of the two different mediums. Experimental data were collected from both a simple ordering method and electrical activity of the brain. Results showed unexpected outcomes indicating that only some of the illusions have a stronger effect in immersive virtual reality, others in monitor based environments while the rest with no significant effects.**

***Index Terms*—virtual reality, visual illusions, perception, human factors, games**

I. Introduction

Visual illusions serve as a powerful window into the brain but it is very difficult to define them accurately since there is a sense in which all of vision is an illusion [1]. They are critical tools for understanding the underlying mechanisms of the brain [1] and represent good adaptations of the visual system to standard viewing situations [2]. Relative distances and depth locations of different parts of an object are often perceived as fluctuating [3].

Our eyes perceive visual stimuli and in some cases this is misinterpreted in our brain. As a result, we perceive altered objects [4] or we can see something that is absent from the original image. The diversity of the illusory response was examined in 32 visual illusions and concluded that no theory of illusions is sufficient [5].

On the other hand, immersive virtual reality (VR) creates the illusion that the viewer is seeing objects in a synthetic space [6]. The role of top-down processing on the horizontal-vertical line length illusion was examined using an ambiguous room with dual visual verticals [7]. Results showed that the line length appeared longer when it was aligned with the direction of the vertical currently perceived by the subject.

Another study introduced apparent self-motion illusions by manipulating optic flow fields during movements [8]. The evaluation of the illusions was performed in different regions of the visual field provided to users. Using psychophysics researchers illustrated that the illusions can affect travel distance judgments in VR.

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The majority of visual illusions are generated by two-dimensional pictures and their motions [9], [10]. But there are not a lot of visual illusions that make use of three-dimensional (3D) shapes [11]. Visual illusions are now slowly making their appearance in serious games and are unexplored in virtual reality. Currently, they are usually applied in the fields of brain games, puzzles and mini games.

However, a lot of issues regarding the perceptual effects are not fully understood in the context of digital games. An overview of electroencephalography (EEG) based brain-computer interfaces (BCIs) and their present and potential uses in virtual environments and games has been recently documented [12].

In this paper we present six different visual illusions (Fig. 1) that are made in 3D. The illusions were designed in such a way so that they can be used in both games (LCD screens) as well as immersive VR. A user-study with 30 healthy participants took place comparing the two different visualisation media.

Results from a simple ordering method showed that two illusions had stronger effect in VR, one in LCD screens and the rest of them no significant difference while the EEG results showed attenuated alpha and theta activity.

The rest of the paper is structured as follows. Section II presents research that was done with illusions and BCIs. None of the papers reported dealt with games and VR. Section III presents the design of the six illusions whereas section IV the experimental methodology. Section V presents our results and section VI the dicsusion. Finally, section VII concludes the paper.

II. Background

According to [1], visual illusions uncover that our thoughts are generated by machinery to which we have no direct access. There has been only a few BCI studies that examined different types of visual illusions and non in immersive VR.

An early approach used functional magnetic resonance imaging (fMRI) to demonstrate an increase in activity in medial temporal (MT) area when participants were exposed to a stationary stimulus undergoing illusory motion [13]. This followed adaptation to stimuli moving in a single local direction and results showed that the cells in human area MT were also direction specific.

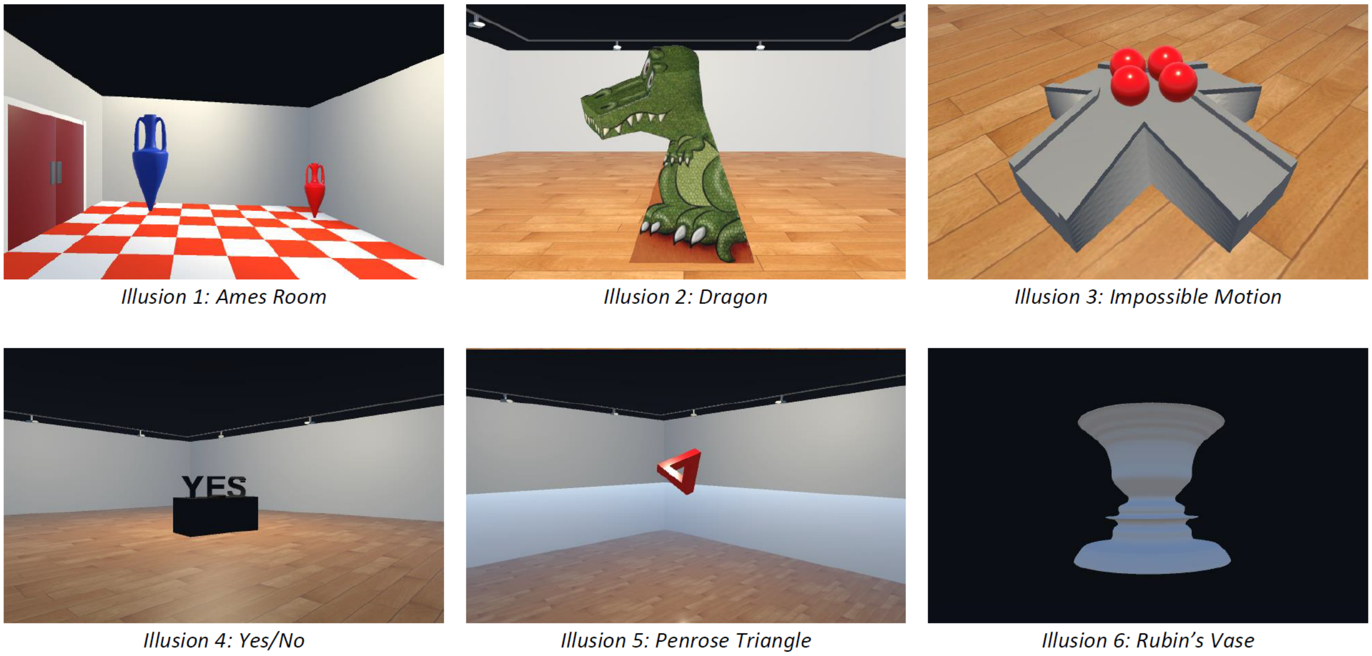

Fig. 1. Overview of the visual illusions examined

In another study, the Thatcher illusion was investigated using event related potentials (ERPs) [14]. Experimental results with sixteen participants showed differences in the neural encoding of Thatcherized and original inverted faces, even though Thatcherization escapes subjective perception in inverted faces. Moreover, unfamiliar line drawings were examined using fMRI scanning and a set of brain areas was detected [15].

The effect of stimulus repetition on the evoked fMRI response depended on whether or not the drawing could be conceived as a coherent three-dimensional structure. A similar study was performed by recording ERPs and reaction time (RT) while subjects classified possible and impossible objects as left- or right-facing [16]. Results showed that RT priming of impossible objects depends on part-based structural encoding, whereas ERP priming most likely reflects contact.

Furthermore, an EEG study compared the relation of the ERP amplitudes to varying sizes of ambiguous Necker cubes [17]. Results showed that low-level visual processing and high-level processing occur in close spatial and temporal vicinity. In another illusion study, where the center of a static wheel stimulus is experienced as flickering, EEG analysis showed that stimulus motion relative to the retina is not crucial to perceive the illusory flicker [18].

The visual illusion effect in the Müller-Lyer illusion tasks was also examined using ERPs and results showed that there were significant differences between mean illusion magnitudes [19]. The moon illusion was investigated using a VR environment and fMRI. Results showed that the brain regions that dynamically integrate retinal size and distance play a key role in generating the moon illusion [20].

Individual illusion magnitude with fifty-nine participants using structural MRI scanning was examined and results found some degree of similarity in behavioral judgments of all tested geometrical illusions, but not between geometrical illusions and non-geometrical, contrast illusion [21]. The magnitude of all geometrical illusions was only correlated in the parahippocampal cortex, but not in other brain areas.

Finally, a behavioral task with 7 participants showed that attentional binding of visual features is performed periodically at approximately 8 Hz and electrical activity of the brain showed a dependence of binding performance on prestimulus neural oscillatory phase [22]. According to the results, the association between perceptual and neural oscillations is triggered by voluntary action.

However, although the literature examined above presents a very clear focus on a particular illusion, there has never been a study comparing different and diverse visual illusions together. The focus of our study is to have an initial understanding of how 3D illusions are compared to fully immersive VR and what are the perceptual differences (if any).

III. Design

A simple but immersive application was developed presenting several optical illusions in three-dimensional space to the user in two media: LCD screen (1920x1080 resolution) and immersive VR. As mentioned before, there are plenty of illusions displayed in two-dimensional space [9], [10]; however, the focus was in illusions that evaluate user's perception in terms of 3D space. Diversity was another important factor while choosing illusions for the experiment. Unlike common optical illusions the majority of 3D optical illusions use perspective to confuse the viewer.

In terms of the design, six different rooms were designed. Each room contains one illusion at a time in a form of an exhibit which is typically situated in the middle of the room. Perspective plays vital role in the perception of the illusions. The illusions are displayed for 4 seconds and afterwards it is rotated to reveal the trick. After 4 seconds, the model returns to its original position. When the animation ends, the object is replaced by the following model in the scene. Most of the illusions were fairly well known and an overview is illustrated in Fig. 1.

A. Illusion 1: Ames Room

Ames room is one of the most famous illusions where there are two persons (or objects) in the opposite corners of a room [23]. A person (or object) looks taller when moving from one corner of the room to another. So, despite both being the same height, they are perceived in different sizes.

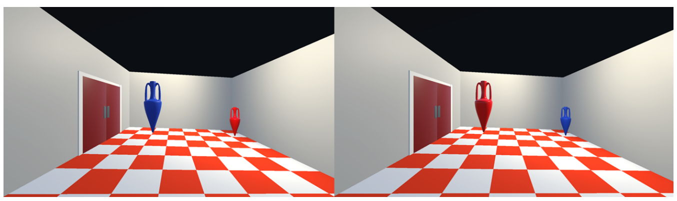

Fig. 2. Ames Room

For the objects to take one another's place, a model of vase was created, as it has similar proportions as human figure commonly used for demonstration of this illusion and it was easy to animate. The model of vases based on old Greek amphorae was created in 3D modeling tool (i.e. Cinema 4D), while the room was created by user with nickname Apos and downloaded from under Creative commons attribution.

B. Illusion 2: Dragon

This illusion was invented by Jerry Andrus and the spectator is presented with a simple dragon model with eyes looking towards him or her [24]. The dragon is concave, but is seen as convex. The interesting thing is that no matter how the viewer moves, the eyes seem to keep following the viewer. Sides of the head are curved from the center towards the viewer giving the illusion that the dragon is followed.

Fig. 3. Dragon

The scene itself contains two models and shadows were disabled as they were suggesting the columns are tilted. A texture was applied on a single square polygon, then the quad was cut to match the template, unnecessary faces were deleted while the rest were bent around marked edges. For the scene, the environment lightning was used, as shadows cast by the upper part of the head was ruining immersion of the illusion.

C. Illusion 3: Impossible Motion

Anti-gravity slopes are series of platforms created by Dr. Sugihara Kokichi performing so-called "impossible motion" [25]. The idea is based on the concept known as "Anomalous pictures", which generates interesting optical illusion to human eyes. In this illusion, slopes look straight only when looking from this specific point. The 3D scene was created using the same procedure as a paper cut model [26].

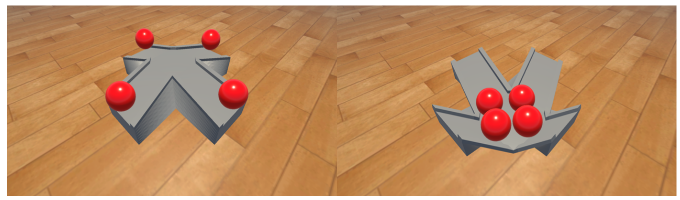

Fig. 4. Impossible Motion

D. Illusion 4: Yes/No

This is not a geometric illusion but a figure stating the word "Yes" but when it is rotated the word slowly turns into opposite "No". The key concept relates to the projections of the 3D object upon an imaginary plane that is perpendicular to the viewer's eye [27]. It was proposed by a Swiss artist called Markus Raetz and it is very popular among artists as not only different words but also shapes can be displayed.

Fig. 5. Yes/No

In the implementation, the scene contains three models in total. A statue with text displaying either 'Yes' or 'No', 'White' or 'Black' and insignias of Rebel Alliance and Galactic Empire from Star Wars.

E. Illusion 5: Penrose Triangle

Penrose Triangle was originally created by Swedish artist Oscar Reutersvärd in 1934 and can be depicted in a perspective drawing, but cannot exist as a solid object [28]. It is considered to be an impossible object as it breaks the rules of Euclidean geometry. The 3D interpretation of Penrose triangle consists of three bars bent in right angle. When viewed from the proper position, the arms seemingly connect, forming a triangle.

The scene contains three models in total. The Penrose triangle, Escher's staircase and a model which looks like a cube when observed from correct position. The room was

Fig. 6. Penrose Triangle

created differently from the rest by adding glass floor revealing another room situated below where the staircase was placed.

F. Illusion 6: Rubin's Vase

Rubin's vase illusion was discovered by Danish psychologist Edgar Rubin. It is believed, the retinal image while observing this illusion is constant, as the observer can see one or other image at any time. Rubin's vase is one of few illusions that work in both 2D and 3D. In this illusion in somecases you perceive the vase and other the faces but can not simply see both of them at once [1].

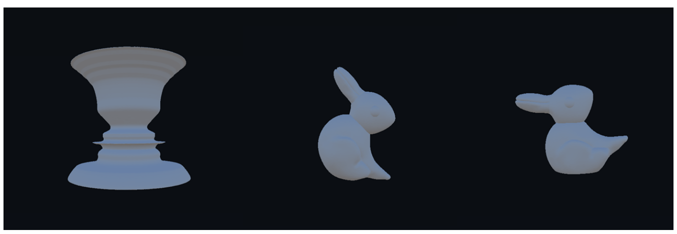

Fig. 7. Rubin's Vase and duck

This scene contains two models. A Rubin's vase and a model in a shape of both rabbit and duck. While the vase remains static, the rabbit figure is being rotated after brief delay to prompt the shape of a duck. For the scene the lighting was disabled and only the model remained illuminated to increase the effect from illusion.

IV. Study

A. Participants

The experiment had between-subject design and was conducted with 30 volunteers: 20 males and 10 females in laboratory conditions. The mean age of the participants was 24 years. The medium for each session was selected randomly; however, the same number of users (N=15) participated for VR and for the LCD.

To reduce the amount of both electromagnetic and audible noise, the testing was held in an air-conditioned room containing only the equipment necessary for the experiment (experimenter was also present in the room). Each session took approximately between 30 to 45 minutes.

B. Experimental Setup

The immersive VR was mediated using the industry standard head-mounted display (HMD) HTC Vive, while the EEG was recorded using Enobio 8 (Neuroelectrics, Spain). EEG

Fig. 8. User participating in the VR experiment

recording concurrent to wearing an HMD is not uncommon, while using HTC Vive for this purpose have been proven feasible in terms of low amounts of noise [29]. For the experiment, EEG was recorded using 8 AgCl electrodes, placed on the following locations according to the standard 10-20 system: P3, O1, O2, P4, F7, F3, F4 and F8.

Electro-conductive gel was applied on each electrode. The common mode sense/driver right leg reference electrode was placed on an earlobe using clip. Signal check and recording was performed using open-source OpenVibe software. Bad quality of signal was resolved by re-attaching the electrode or adding more gel, while the high amount of noise could be typically fixed by reattaching the reference electrode.

C. Procedure

In the beginning, each participant was briefed about the experiment and its requirements. Participants were then asked to read and fill in the consent form. Next, demographic information was collected, such as age, gender or occupation.

After collecting data from the initial forms, the EEG device and the HMD was put on (see Figure 8). Signal re-check followed after the HMD was on. Regarding the instructions for EEG recording, participants were instructed to remain calm and not to move during the optical illusions presentation (including head movement), as it creates artifacts in EEG signals. For the same reason, they were also asked to reduce blinking. Nevertheless, it was made clear that blinking and slight adjustments to body posture was acceptable between the scenes. The length of the EEG recording was fixed, taking approximately 5 minutes.

After the experiment, a single-page ranking form was given to the participants to order the visual illusions according to their believability. These values were converted to points for the purposes of analysis (1 meaning poorest rating, while 6 was the highest possible rating). The order of the illusions was randomised.

D. EEG signal processing

The information extracted from the EEG signals was the change in band powers in reaction to showing the trick behind each optical illusion. It was computed as the difference of the band powers in the part where scene was rotated to reveal the trick, to the band powers in the initial part where the illusion was presented (before the trick was shown). It is worth-mentioning, that EEG was not measured after rotating the illusion back to the initial state at the end of each scene.

For this purpose, the signals were cleaned using down-sampling to 100 Hz (to clean the 50 Hz line noise) and high-pass filtering at 1.5 Hz (to clear the DC drift). Further cleaning was performed with specialized algorithm (artifact subspace reconstruction [30]). Frequency spectra of the initial part (first 4 seconds in each presented illusion) and the revealing part of each illusion type (also 4 seconds long) were computed using *spectopo* function in EEGLAB [31]. Analyzed frequency bands were the alpha, beta, and theta ranges. Event-related (de)synchronization (the revealing part − the initial part) in each band was computed in percents.

Spatially, the following three areas of interest (frontal, parietal, and occipital lobe) were averaged from the utilized EEG sensors. The band power changes were further averaged over the illusion type in cases of multiple optical illusions in one type.

E. Statistical analysis

The main goal of the analysis was to determine the differences between the LCD and VR media, in terms of both the ordering method and the extracted band power changes from the EEG signals. Firstly, the differences between rating of each illusion were tested, as well as the differences in EEG band power spectra per frequency band (alpha, beta, theta) and the area of interest (frontal, parietal, occipital).

EEG results were examined also per-illusion, and a within-subject investigation into the differences in average EEG responses on the two strongest and the two weakest illusions was performed. Non-parametric Wilcoxon rank sum test was used to find the differences, and the data were analyzed using R software.

V. Results

A. Rating Results

1) Rating of the illusions: The strongest illusion in the VR was illusion 4 (average 5.00 points, SD = 1.13) and the weakest was illusion 3 (average 2.07 points, SD = 1.10). On the LCD screen, participants rated as the strongest the illusion 5 (average 4.73 points, SD = 1.28) and the weakest was illusion 2 (average 2.07 points, SD = 1.10). Boxplots with rating of each illusion per medium is showed in Figure 9.

2) Differences between the VR and LCD: In total, three illusions were significantly differently rated in the ordering report. Illusion 2 was stronger in the VR (average 3.40 points) than on the LCD screen (average 2.07 points) with W = 166.5, p = 0.023. The largest difference was present in illusion 3, which was stronger on the LCD screen (average 4.00 points) than in the VR (average 2.07 points) with W = 42 and p = 0.003). Illusion 4 was again stronger in the VR (5.00 points on the average) than on the LCD (3.80 points on average) with W = 163.5 and p = 0.031.

B. EEG Results

1) General trends: The average band power change of EEG theta and alpha bands per illusion, medium, and scalp region is illustrated in Figure I. Attenuation of rhythmical neural activity was observed as the effect of all presented illusion in all frequency bands, except for beta, where the spectrum changes were $< +-1\%$ in all examined scalp locations. The strongest attenuation was found in occipital theta (-36.55% on average), followed by frontal theta (-23.87% on average). These values represent average band power changes; results in terms of differences between the VR and LCD are presented in the next subsection.

Event-related theta oscillations (between 4–7 Hz) are important for top-down regulated processes including: focused attention [32], [33], control mechanisms in working memory [34] or executive functions [35]. According to some studies, theta oscillations seem to be unrelated to perceptual switches [36], [37]. Alpha band reduction is common during visual perception [38], while beta band is linked to mainly to cognitive processing.

2) Differences in EEG spectra: The strongest effect was observed in the average response to the optical illusions, manifested by the change of alpha frequency neural oscillations over the occipital lobe (the seat of the visual cortex). In VR, there was a significantly stronger weakening of the alpha oscillation (-27.25% on average), which was largely missing with the LCD presentation (-1.39%). This effect was present with W = 57 and p = 0.021.

After examining each of the illusions separately, it was found that the strongest difference in attenuation of the occipital alpha was present surprisingly in the first (one of the weakest) optical illusions (W = 8, p = 0.000), where VR produced the attenuation (-68.19% on average) and LCD did not (+11.24% on average).

Illusion 4 produced attenuation of the theta activity in the frontal lobe, which was significantly stronger in the VR (average change -69.31%) than on the LCD (-23.90%), W = 43, p = 0.034. Similar difference in attenuation of the theta spectrum was found over the parietal cortex during illusion 6. In VR with average change of -30.18% and on the LCD display with negligible average change equal to +2.13% (W = 45 and p = 0.044).

Test of within-subject differences in EEG spectra with respect to the strongest and the weakest illusion reported by the participant was performed, but no significant difference were found. This is probably due to the different nature of the presented illusions, not allowing to find a common neural representation across the different kinds.

VI. Discussion

The rating responses showed that 2 out of 6 illusions (illusions 2 and 4) had stronger effect in immersive VR compared to LCD screen. In illusion 2, the effect is evident irrespective of how the viewer moves (the eyes seem to keep following the user). In illusion 4, it also seems that movement does not play a significant role.

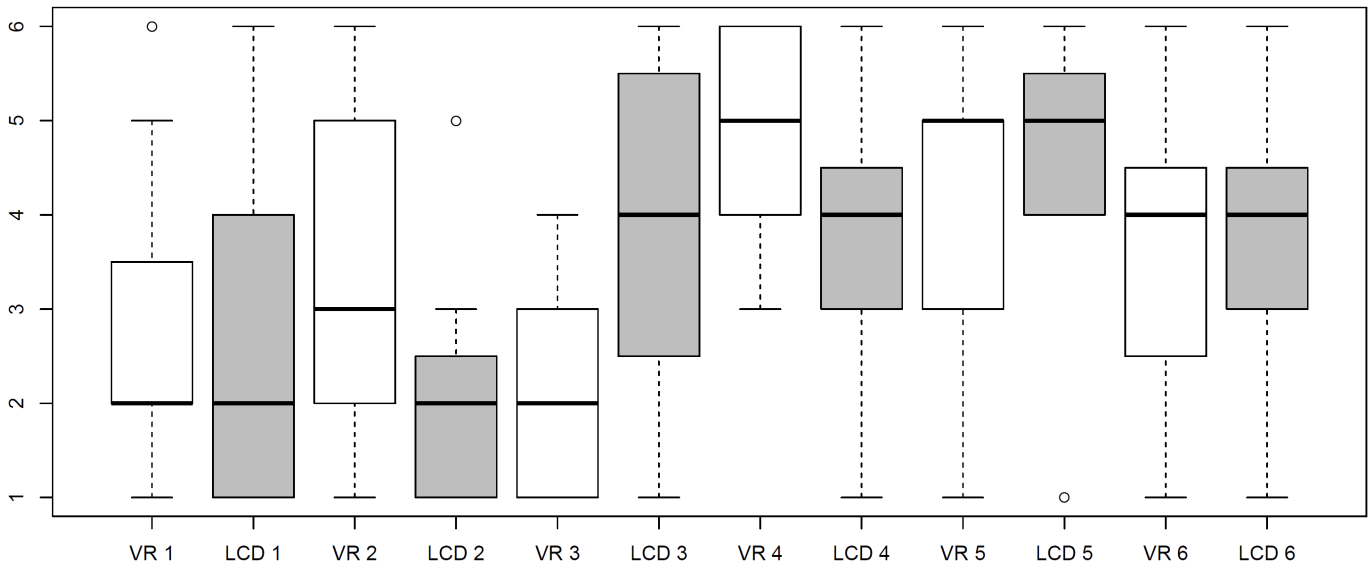

Fig. 9. Boxplot showing rating of the the six types of illusions per medium (VR, LCD)

Illusion	Frontal Theta	Parietal Theta	Occipital Theta	Frontal Alpha	Parietal Alpha	Occipital Alpha
Illusion 1 (VR)	-76.75	22.86	-61.58	-14.86	-29.92	-68.19
Illusion 1 (LCD)	-43.94	-3.38	13.57	10.75	-1.96	11.24
Illusion 2 (VR)	-20.30	10.47	-29.21	-16.90	-11.73	-14.88
Illusion 2 (LCD)	-31.98	-8.59	-23.80	7.30	-1.02	14.85
Illusion 3 (VR)	-28.00	-33.65	-48.49	-8.68	1.93	7.17
Illusion 3 (LCD)	-18.91	-22.47	-30.72	10.40	-4.30	12.22
Illusion 4 (VR)	-69.31	-5.77	-37.58	-10.65	-3.77	-18.63
Illusion 4 (LCD)	-23.90	-2.62	-38.10	-4.79	-25.26	-22.43
Illusion 5 (VR)	-25.99	-9.31	-44.14	-3.79	-15.32	-20.70
Illusion 5 (LCD)	4.23	-24.19	-33.56	-20.53	-22.62	5.82
Illusion 6 (VR)	10.37	-30.18	-41.81	-24.23	-45.24	-41.30
Illusion 6 (LCD)	0.64	2.13	-14.72	-19.31	-40.59	-28.23

TABLE I
AVERAGE BAND POWER CHANGE (IN PERCENTS) OF EEG THETA AND ALPHA BANDS PER ILLUSION, MEDIUM, AND SCALP REGION.

On the contrary, the 3rd illusion was stronger in LCD screen where positioning is crucial. In particular, the effect (slopes look straight) is evident only when looking from this specific point of view. This might have been the reason that LCD screen created the strongest effect. The remaining illusions (illusions 1, 5 and 6) did not have any noticeable difference and the common aspect is that movement does not have a significant effect.

Theta and alpha neural oscillations tended to decrease their band powers in course of most of the optical illusions. Alpha band power is often used as a marker of inactivity for the underlying brain areas [39], while decrease of alpha band oscillations signifies more ongoing neural activity. Such an explanation would make a clear sense in case of the occipital areas (consisting largely of visual cortex), which is active during visual perception (a well-known marker of visual cortex inactivity is strengthened EEG alpha power after the subject closes his/her eyes [40]).

Oscillations in the alpha range recorded over the central and parietal regions often reflects the sensory integration processes, such as tasks requiring coordination of vision and attention [41], [42]. Inter-sensory inconsistency introduced by watching the illusory scenes can likely be a cause of the observed parietal alpha reductions.

Theta band oscillations are connected to attention and memory processing. In general, increased theta is linked to decreased executive control processes (mind-wandering in participants) [43]) and stronger default mode network processing [44]. Increased frontal theta together with increased frontal and occipital alpha band powers is also known to be correlated to mental fatigue [45]. Based on this, it does not seem that our observations in the theta spectrum reflect more than growing fatigue during observational tasks. Further changes in the theta range might be caused by perception of the bi-stable figures and illusions causing perceptual switches (last three illusions) [37].

There are several limitations on the study. First of all, there is no control group (with non-illusory scenes), which would allow for a more elaborate analysis of the ranking method and EEG signals. Another limitation is that the ordering method that was used does not allow a tie. Moreover, more experimental data would be beneficial to the understanding of the illusions, including presence, immersion and cognitive workload.

Finally, to understand better the diversity of illusions, a much bigger sample might help to make some concrete generalisations, such as establishing correlations between the responses and the recorded neurophysiological signals. More detailed investigation in the future would elucidate the relationship between observed changes in EEG band powers and subjective strength of the optical illusions.

VII. Conclusions

Overall our findings contribute to obtaining a better understanding of the mechanisms behind visual illusions in immersive VR. As [5] pointed out, there is a diversity of the illusory response in visual illusions and our experimental results follow the same pattern. We examined six different 3D visual illusions and compared them in immersive VR versus LCD screen. Results from ranking showed that two illusions had stronger effect in VR, one in LCD screens and the rest of them had no significant effect.

The EEG results showed attenuated alpha and theta activity. Results in the alpha range, especially over the occipital cortex, demonstrate engagement of the visual processing during the perception of the illusions. Parietal alpha reductions observed during the experiment could be directly related to the neural manifestations of perceiving and processing of the optical illusions. Reduced theta oscillations are unlikely a direct effect of the experimental intervention.

Although the study presents preliminary results, it provides insight for further research. Games companies as well as VR display manufacturers might want to know how to create strong interesting effects. The next step is to focus on the illusions that produced stronger effect in VR and put them in a gaming context. A large scale evaluation will be performed to examine how the illusions create strong effects.

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References

[1] D. Eagleman, *Incognito : the secret lives of the brain*, 1st ed. New York, NY: Pantheon Books, 2011.

[2] M. Bach and C. M. Poloschek, "Optical illusions," *Advances in Clinical Neuroscience and Rehabilitation*, vol. 6, no. 2, May-June 2006. [Online]. Available: https://www.acnr.co.uk/pdfs/volume6issue2/v6i2visual.pdf

[3] M. Luckiesh, *Visual Illusions: Their Causes, Characteristics and Applications*. New York, NY: D. Van Nostrand Company, 2011.

[4] C. Stangor and J. Walinga, *Introduction to Psychology*. 1st Canadian Edition. Victoria, B.C.: BC campus, 2014. [Online]. Available: https://opentextbc.ca/introductiontopsychology

[5] M. S. Lindauer, "Extent of illusory effects for 32 illusions," *Perceptual and Motor Skills*, vol. 36, no. 3, pp. 887–894, 1973, pMID: 4704338. [Online]. Available: https://doi.org/10.2466/pms.1973.36.3.887

[6] J. P. Wann, S. Rushton, and M. Mon-Williams, "Natural problems for stereoscopic depth perception in virtual environments," *Vision Research*, vol. 35, no. 19, pp. 2731 – 2736, 1995. [Online]. Available: http://www.sciencedirect.com/science/article/pii/004269899500018U

[7] F. W. Mast and C. M. Oman, "Top-down processing and visual reorientation illusions in a virtual reality environment," *Swiss Journal of Psychology / Schweizerische Zeitschrift für Psychologie / Revue Suisse de Psychologie*, vol. 63, no. 3, pp. 143–149, 2004.

[8] G. Bruder, F. Steinicke, P. Wieland, and M. Lappe, "Tuning self-motion perception in virtual reality with visual illusions," *IEEE Transactions on Visualization and Computer Graphics*, vol. 18, no. 7, pp. 1068–1078, 2012.

[9] J. Ninio and F. Philip, *The Science of Illusions*. Ithaca: Cornell University Press, 2001.

[10] J. T. Unruh, *Impossible Objects : Amazing Optical Illusions to Confound and Astound*. Sterling Publishing Co., Inc., 2002.

[11] K. Sugihara, "Design of solids for antigravity motion illusion," *Computational Geometry*, vol. 47, no. 6, pp. 675 – 682, 2014, 27th European Workshop on Computational Geometry (EuroCG 2011). [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0925772113001752

[12] B. Kerous and F. Liarokapis, "Brain-computer interfaces - A survey on interactive virtual environments," in *8th International Conference on Games and Virtual Worlds for Serious Applications, VS-GAMES 2016, Barcelona, Spain, September 7-9, 2016*. IEEE Computer Society, 2016, pp. 1–4. [Online]. Available: https://doi.org/10.1109/VS-GAMES.2016.7590339

[13] R. B. Tootell, J. B. Reppas, A. M. Dale, R. B. Look, M. I. Sereno, R. Malach, T. J. Brady, and B. R. Rosen, "Visual motion aftereffect in human cortical area mt revealed by functional magnetic resonance imaging," *Nature*, vol. 375, no. 6527, pp. 139–141, 1995.

[14] C.-C. Carbon, S. R. Schweinberger, J. M. Kaufmann, and H. Leder, "The thatcher illusion seen by the brain: an event-related brain potentials study," *Cognitive Brain Research*, vol. 24, no. 3, pp. 544 – 555, 2005. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0926641005000789

[15] C. Habeck, H. J. Hilton, E. Zarahn, T. Brown, and Y. Stern, "An event-related fmri study of the neural networks underlying repetition suppression and reaction time priming in implicit visual memory," *Brain Research*, vol. 1075, no. 1, pp. 133 – 141, 2006. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0006899305016823

[16] D. Friedman and Y. M. Cycowicz, "Repetition priming of possible and impossible objects from erp and behavioral perspectives," *Psychophysiology*, vol. 43, no. 6, pp. 569–578, 2006. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1469-8986.2006.00466.x

[17] J. Kornmeier, M. Pfäffle, and M. Bach, "Necker cube: stimulus-related (low-level) and percept-related (high-level) eeg signatures early in occipital cortex," *Journal of vision*, vol. 11, no. 9, p. 12, 2011. [Online]. Available: https://doi.org/10.1167/11.9.12

[18] R. Sokoliuk and R. VanRullen, "The flickering wheel illusion: when α rhythms make a static wheel flicker," *The Journal of Neuroscience*, vol. 33, no. 33, p. 13498–13504, 2013.

[19] S. Zhang, X. Du, X. Wu, D. Wei, M. Zhang, and J. Qiu, "Spatiotemporal cortical activation underlies the müller–lyer illusion," *Neuroreport*, vol. 24, pp. 956–961, 09 2013.

[20] R. Weidner, T. Plewan, Q. Chen, A. Buchner, P. Weiss, and G. Fink, "The moon illusion and size-distance scaling-evidence for shared neural patterns," *Journal of cognitive neuroscience*, vol. 26, pp. 1871–1872, 02 2014.

[21] V. Axelrod, D. S. Schwarzkopf, S. Gilaie-Dotan, and G. Rees, "Perceptual similarity and the neural correlates of geometrical illusions in human brain structure," *Scientific Reports*, vol. 7, no. 39968, 2017. [Online]. Available: https://www.nature.com/articles/srep39968

[22] R. Nakayama and I. Motoyoshi, "Attention periodically binds visual features as single events depending on neural oscillations phase-locked to action," *Journal of Neuroscience*, vol. 39, no. 21, pp. 4153–4161, 2019. [Online]. Available: https://www.jneurosci.org/content/39/21/4153

[23] R. L. Gregory, "The intelligent eye," *Weidenfeld and Nicolson, London*, 1970.

[24] K. Kisimoto and K. Iizasa, "3D Viewing: Odd Perception - Illusion? reality? or both?" in *AGU Fall Meeting Abstracts*, vol. 2008, Dec. 2008, pp. ED23B–0644.

[25] K. Sugihara, “A characterization of a class of anomalous solids,” *Interdisciplinary Information Sciences*, vol. 11, no. 2, pp. 149–156, 2005.

[26] D. Stover, “A paper-thin illusion: Make your own magnetlike slopes [slide show],” *Scientific American*, 2011.

[27] I. Symeonidou, “Anamorphic experiences in 3d space: Shadows, projections and other optical illusions,” *Nexus Network Journal*, vol. 18, pp. 779–797, 2016.

[28] T. Pappas, “The impossible tribar,” *The Joy of Mathematics*, p. 13, 1989.

[29] S. Hertweck, D. Weber, H. Alwanni, F. Unruh, M. Fischbach, M. E. Latoschik, and T. Ball, “Brain activity in virtual reality: Assessing signal quality of high-resolution eeg while using head-mounted displays,” in *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2019, pp. 970–971.

[30] C.-Y. Chang, S.-H. Hsu, L. Pion-Tonachini, and T.-P. Jung, “Evaluation of artifact subspace reconstruction for automatic eeg artifact removal,” in *2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE, 2018, pp. 1242–1245.

[31] A. Delorme and S. Makeig, “Eeglab: an open source toolbox for analysis of single-trial eeg dynamics including independent component analysis,” *Journal of neuroscience methods*, vol. 134, no. 1, pp. 9–21, 2004.

[32] J. Polich, “Updating p300: An integrative theory of p3a and p3b,” *Clinical neurophysiology : official journal of the International Federation of Clinical Neurophysiology*, vol. 118, pp. 2128–2148, 11 2007.

[33] B. R. Cahn, A. Delorme, and J. Polich, “Event-related delta, theta, alpha and gamma correlates to auditory oddball processing during vipassana meditation,” *Social cognitive and affective neuroscience*, vol. 8, no. 1, pp. 100–111, 2013.

[34] P. Sauseng, B. Griesmayr, R. Freunberger, and W. Klimesch, “Control mechanisms in working memory: A possible function of eeg theta oscillations,” *Neuroscience and Biobehavioral Reviews*, vol. 34, no. 7, pp. 1015 – 1022, 2010, binding Processes: Neurodynamics and Functional Role in Memory and Action. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0149763409001973

[35] R. Huster, S. Enriquez-Geppert, C. Lavallee, M. Falkenstein, and C. Herrmann, “Electroencephalography of response inhibition tasks: Functional networks and cognitive contributions,” *International journal of psychophysiology : official journal of the International Organization of Psychophysiology*, vol. 87, pp. 217–233, 08 2012.

[36] W. Ehm, M. Bach, and J. Kornmeier, “Ambiguous figures and binding: Eeg frequency modulations during multistable perception,” *Psychophysiology*, vol. 48, no. 4, pp. 547–558, 2011. [Online]. Available: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1469-8986.2010.01087.x

[37] H. Nakatani and C. Leeuwen, “Individual differences in perceptual switching rates; the role of occipital alpha and frontal theta band activity,” *Biological cybernetics*, vol. 93, pp. 343–354, 12 2005.

[38] C. Babiloni, F. Vecchio, A. Bultrini, G. Luca Romani, and P. M. Rossini, “Pre-and poststimulus alpha rhythms are related to conscious visual perception: a high-resolution eeg study,” *Cerebral cortex*, vol. 16, no. 12, pp. 1690–1700, 2006.

[39] H. Laufs, K. Krakow, P. Sterzer, E. Eger, A. Beyerle, A. Salek-Haddadi, and A. Kleinschmidt, “Electroencephalographic signatures of attentional and cognitive default modes in spontaneous brain activity fluctuations at rest,” *Proceedings of the National Academy of Sciences*, vol. 100, no. 19, pp. 11 053–11 058, Sep. 2003. [Online]. Available: https://www.pnas.org/content/100/19/11053

[40] E. Niedermeyer *et al.*, “The normal eeg of the waking adult,” *Electroencephalography: basic principles, clinical applications and related fields*, vol. 20, no. 4, pp. 149–173, 1999.

[41] K. Gramann, J. Onton, D. Riccobon, H. J. Mueller, S. Bardins, and S. Makeig, “Human brain dynamics accompanying use of egocentric and allocentric reference frames during navigation,” *Journal of cognitive neuroscience*, vol. 22, no. 12, pp. 2836–2849, 2010.

[42] B. V. Ehinger, P. Fischer, A. L. Gert, L. Kaufhold, F. Weber, G. Pipa, and P. König, “Kinesthetic and vestibular information modulate alpha activity during spatial navigation: a mobile eeg study,” *Frontiers in human neuroscience*, vol. 8, p. 71, 2014.

[43] D. van Son, F. M. De Blasio, J. S. Fogarty, A. Angelidis, R. J. Barry, and P. Putman, “Frontal eeg theta/beta ratio during mind wandering episodes,” *Biological psychology*, vol. 140, pp. 19–27, 2019.

[44] R. Scheeringa, M. C. Bastiaansen, K. M. Petersson, R. Oostenveld, D. G. Norris, and P. Hagoort, “Frontal theta eeg activity correlates negatively with the default mode network in resting state,” *International journal of psychophysiology*, vol. 67, no. 3, pp. 242–251, 2008.

[45] E. Wascher, B. Rasch, J. Sänger, S. Hoffmann, D. Schneider, G. Rinkenauer, H. Heuer, and I. Gutberlet, “Frontal theta activity reflects distinct aspects of mental fatigue,” *Biological psychology*, vol. 96, pp. 57–65, 2014.