Themes in Science & Technology Education, 9(2), 83-91, 2016

Cognitive load and attentional demands during objects' position change in real and digital environments

Georgios K. Zacharis, Tassos Anastasios Mikropoulos, Katerina Kalyvioti
gzacharis@uoi.gr, amikrop@uoi.gr, kkaliviotis@yahoo.gr

Educational Approaches to Virtual Reality Technologies Laboratory
University of Ioannina, Greece

Abstract. Studies showed that two-dimensional (2D) and three-dimensional (3D) educational content contributes to learning. Although there were many studies with 3D stereoscopic learning environments, only a few studies reported on the differences between real, 2D, and 3D scenes, as far as cognitive load and attentional demands were concerned. We used electroencephalographic measurements to study and compare the theta (θ), alpha (α), beta (β) and gamma (γ) frequency bands of 36 adult female participants. The participants observed three environments with the same content, a real, a 3D and a 2D environment. Brain activity was recorded for each environment and their two versions, i.e., a before version and an after version, where the position of specific objects changed. Our study's findings indicated that all participants perceived the three environments, their depicted objects, and the change of the objects' position. The participants' cognitive load and attentional demands were higher in all environments before the change of the objects' position. Working memory load, working and spatial memory, were also higher in the two digital environments (3D and 2D) before the change of the objects' position. However, the opposite was observed in the case of the real environment. This was attributed to the participants observing the real environment firstly. Overall, we propose that empirical studies with biometric data on cognitive load and attentional demands will support the design of better learning environments.

Keywords: Brain activity, EEG, digital environment, 3D, 2D, cognitive load, attentional demands

Introduction

Human vision has the ability of stereo vision through mechanisms for processing three-dimensional (3D) images (van der Land et al., 2013). Virtual Reality (VR) technologies, with their main characteristics being the 3D spatial representations, have emerged in many aspects of life and especially in education. In Virtual Environments (VEs) and generally in digital environments, the optical sensing pathway was usually considered as the most important and decisive input. Visual (optical) awareness was a complex perceptual process that took place when processing real and digital data -it organized and linked information from different sides of the visual scene.

Stereoscopic vision was an important factor for the development of visuospatial skills, the understanding of science and visually guided reaching tasks. In addition, stereoscopic vision improved performance for tasks in 3D environments (Arsenault & Ware, 2004) and was crucial for remote learning methods (Kesim & Ozarslan, 2012). Stereoscopy, and the sense of depth were among the main characteristics of VR (Alexander, Conradi & Winkelholz, 2003), and contributed to its learning benefits. Dalgarno & Lee (2010) reported that VEs and 3D simulations provided to educators the possibility of a rich learner engagement, the ability to explore, construct, and manipulate virtual objects, as well as the ability to represent difficult metaphorical ideas. Stereoscopy and 3D perception also contributed to conceptual learning, positive learning outcomes (Salzman et al., 1999; Trindade, Fiolhais & Almeida, 2002; Wu & Shah, 2004) and the perception of the world in Educational Virtual Environments (EVEs) (Thompson, Thompson & Wenqing, 2007). Furthermore, stereoscopy in immersive EVEs supported the effective memorization and had a possible improvement in the performance of the abstract mental activity (Ragan et al., 2010).

Mental effort, defined as "the amount of cognitive resources allocated to learning" in Paas et al. (2005), and cognitive load, defined as "a multidimensional construct representing the load that performing a particular task imposes on the learner's cognitive system" (Paas et al., 2003), were also important parameters in learning environments' design. These parameters were usually measured by using subjective methods such as questionnaires, and less often, by physiological measures. More specifically, few studies have measured brain activity and compared between real and digital (2D or 3D) environments (Dan & Reiner, 2016).

Mikropoulos (2001) reported lower theta activity in the frontal lobes, and subsequently less mental effort, in a virtual environment when compared to an identical real one. Fink et al. (2005) reported "[…] the correlations between lower and upper alpha band ERD systematically decline as task demands increase". Their results showed that when the task demands increased, the lower1 alpha band decreased over the frontal and central lobes, while this had an opposite effect over the parietal and occipital lobes. Holm et al. (2009) showed that the cognitive load index, defined as the ratio of frontal theta to parietal alpha activity (thetaFz/alphaPz), increased with the task demands.

Attention, selective attention, attentional load, visual attention, and attentional demands, i.e. "factors that increase […] the amount of mental effort needed in a situation by requiring prolonged or intense use of directed attention", are associated with cognitive load (Jansen & Keller, 1998). Researchers used EEG techniques for their measurements. Fink et al. (2005) corroborated the findings that the lower alpha bands (~6–8Hz and ~8–10Hz) reflected attentional demands, while the upper alpha (~10–12Hz) reflected specific task demands. Environments that required visual attention showed suppression of alpha activity, which was greater in the occipital lobes (Thut et al., 2006; Worden et al., 2000). Rouhinen et al. (2013) reported that attentional load resulted in theta band suppression and strengthening of gamma waves in frontoparietal and occipital regions. Maurer et al. (2015) showed that frontal midline theta activity increased with working memory load, while lower alpha decreased when the subjects memorized unfamiliar symbols.

Few studies reported on the differences recorded between real, 3D and 2D scenes regarding brain activity in general. Moore & Engel (2001) reported in an fMRI study, that neural activity increased in the lateral occipital region during the presentation of 3D shapes in comparison with 2D shapes. Huang & Liu (2012) studied mental rotation strategies during the identification of 3D and 2D chemical formulas in an Event-Related Potentials experiment. They reported that participants used similar strategies, both in 3D and 2D structures, without presenting differences between 3D and 2D. Zacharis, Mikropoulos & Priovolou (2013) studied the stereoscopic perception in female participants in real and virtual environments. Their results showed that theta, alpha, beta and gamma signals "indicate that stereoscopic 3D virtual environments seem to approximate the real ones as far as it regards the cognitive processes they cause. Three-dimensional stereoscopic environments increase users' attention over the 2D and cause less mental effort". Recently, Dan & Reiner (2016) studied the cognitive load index (thetaFz/alphaPz) during the observation of a paper folding activity presented in 2D and 3D videos. They found that the cognitive load index was higher during the 2D presentation. Moreover, the average theta power of frontal theta (Fz) was larger in 2D, while the average alpha power of parietal (Pz) was similar for both–conditions during a simple task and larger in the 3D presentation during a complex task.

Literature also showed that differences in mental effort and attention do exist between real, 3D and 2D environments (Dan & Reiner, 2016; van der Land et al., 2013; Zacharis at al., 2013). Moreover, and to the best of our knowledge, there is no evidence of brain activity in regards to changes that took place in the layout of the displayed environments. Our work presented a comparative study of electric brain signals in female adult participants during the observation of three environments (a real, a 3D, and 2D), and their respective two (before/after) versions.

Method

The research objective of the present study was to explore differences in brain activity connected with cognitive load and attentional demands, when certain changes took place in three environments with the same content.

Participants

Thirty-six female volunteers (all undergraduate students in teaching), aged 19 to 22 years old (Mean=19.61, SD=1.51), participated in the study. The sample was the same as in Zacharis et al. (2013), and the alpha rhythm of the participants was normal (8–12Hz, 10Hz peak). The study conformed to the code of ethics of the University of Ioannina, Greece.

Real and digital environments

Three sets of environments, a real, a 3D, and a 2D were developed for the needs of this study. Each environment depicted of a desk with a computer monitor, a keyboard, a mouse, a pair of headphones and speakers, a web camera, a microphone, a memory stick, two books, and a CD-ROM disk, all placed on its surface (Figure 1). There were two versions for each environment, the initial (environment 0), and another one where the position of three specific objects (a web camera, a USB stick, and a CD-ROM) changed (environment 1).

Thus, the three sets of the environments were: real environment before (Real 0)/real environment after (Real 1), 3D environment before (3D 0)/3D environment after (3D 1), 2D environment before (2D 0)/2D environment after (2D 1). The 3D digital environment was developed in Autodesk 3ds Max 2010. It was displayed on a 22" stereoscopic LCD monitor (refresh rate of 120Hz), and the participants wore a pair of 3D active glasses. The 2D environment was also displayed on the same monitor. The participants observed the initial version of the real environment (Real 0) firstly, which was then followed by a new, after the change, version (Real 1). Next, the 3D environment was observed in its initial (3D 0) and after (3D 1) version. Lastly, the participants observed the 2D environments, also in its two versions (2D 0 and 2D 1).

Procedure

The participants observed each environment from a one-meter distance, closed their eyes briefly and as needed, the environment changed, they opened their eyes, and observed the next version. The participants also closed their eyes between each of the three environments. The EEG recordings were repeated 10 times for each of the environments and their versions.

Figure 1. The two versions of the 3D stereoscopic environment (3D 0, 3D 1). The image on the right shows the environment after the objects' position change (3D 1)

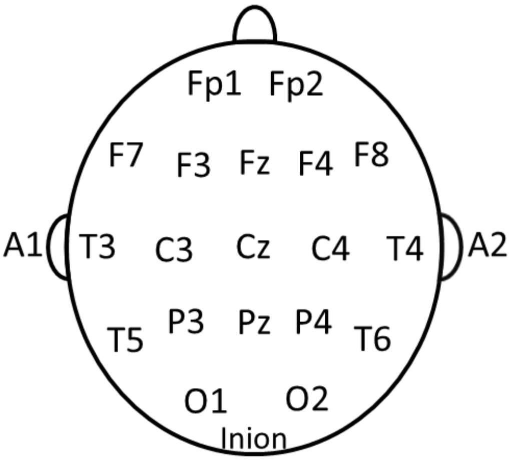

Figure 2. The 10-20 International Electrode Placement System layout

The experimental setup was the same as the one described in Zacharis et al. (2013). The electric brain signals were recorded through an electrode cap, and the recording was based on the 10-20 International Electrode Placement System layout. Brain signals were measured from the pre-frontal (Fp1, Fp2) frontal (F7, F3, Fz, F4, F8), central (C3, Cz, C4), temporal (T3, T4, T5, T6), parietal (P3 Pz, P4), and occipital (O1, O2) lobes (Figure 2). The electrodes reference was at the ear lobe, and the ground electrode was placed on the forehead. Theta (θ, 4–7Hz), alpha (α, 8–12Hz), beta (β, 13–32Hz), and gamma (γ, 33–48Hz) frequency bands were studied. The under study signals were averaged per environment and participant. Grand means were calculated for each environment, and across all subjects.

Results and discussion

The participants stated that they perceived the change in the objects' position in all three environments (i.e., real environment, 3D environment, and 2D environment). They also conveyed to the researchers their sense of depth perception, while viewing the digital stereoscopic 3D environment. Moreover, and maintaining the same topology for the four rhythms under study (i.e., θ, α, β, and γ; Figure 3,), the following were noted regarding the three environment sets (i.e., before/after version of each environment). Table 1 shows the statistically significant power differences ($p < .05$) for the three sets of environments. Alpha activity was measured to be diffused after the change in the objects' position; this finding indicated general brain activation. The strong beta activity recorded in the frontal, parietal and O1 lobes before the change, was an additional indication of cognitive load.

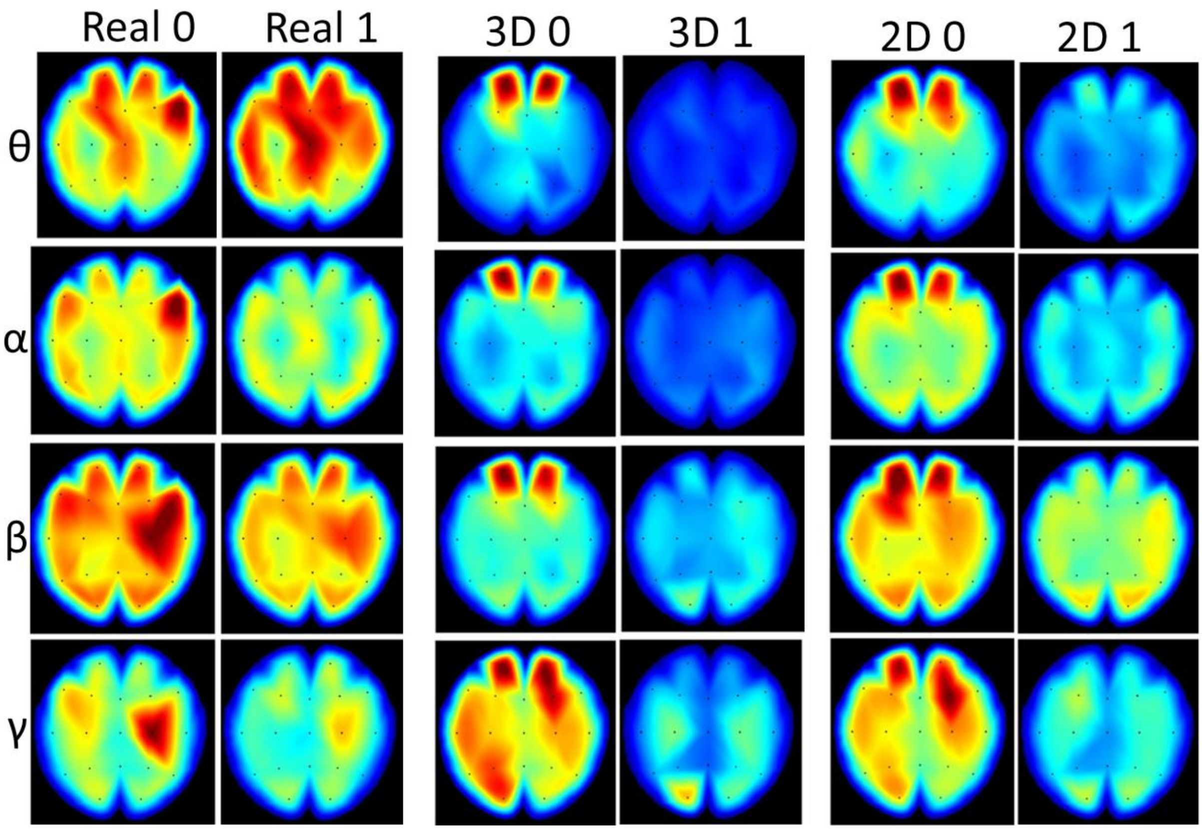

Figure 3. Brain maps for the three sets of environments, before (0) and after (1) the change in objects' positions (warm colours represent high power values; cool colours represent low power values). The power values (μV²) of the EEG signals are normalized for each pair of the brain maps

It was noted that the higher cognitive load, observed in all environments before the change, was commensurate with a higher cognitive load index (thetaFz/alphaPz) (Holm et al., 2009). However, the observed cognitive load appeared to reduce after the change (Rouhinen et. al., 2013), while a lower beta activity in the frontal lobes indicated a relaxation response after the objects' position change (Jacobs et al., 1996).

Participants' performance in the real environment

In regards to the real environment, participants' theta activity was higher after the change of the objects' position (Real 1). This supported that the participants perceived the change in the real environment (Gruber et al., 2008), and engaged in tasks involving working and spatial memory after the change in objects' position (Bastiaansen & Haggort, 2003). Additionally and after the change in the objects' position, alpha signals were stronger in the occipital lobes, which indicated less mental effort and attentional demands. The aforementioned results corroborated by the higher gamma activity recorded before the change. Finally, an interesting finding, as it was only observed in the case of the real environment (Table 1, Real 0), was that participants showed less attentional load after the change of the objects' position (Rouhinen et al., 2013). This was opposed to the two digital environments (the 3D and 2D environments), where the signals' power was significantly higher before the change in the objects' position.

Participants' performance in the digital environments

Theta signals, recorded all over the participants' scalp, were found to be statistically higher for both digital environments before the changes in objects' position (Table 1). A working memory load was suggested by the recorded high frontal midline activity (Maurer et. al., 2015). Moreover, and contrary to respective observations for the real environment, alpha signals were stronger in the occipital lobes in the case of the digital environments before the change (Klimesch, 1999; Donner et al., 2007). This finding indicated less mental effort and attentional demands. In addition, the aforementioned results corroborated by the higher gamma activity noted before the change of the objects' position. On that note, and for the before (0) version of the 3D environment, the observation of a higher cognitive load was consistent with the recorded increase of beta rhythms (Rouhinen et. al., 2013). Lastly, the participants showed less attentional load after the change of the objects' position (Rouhinen et. al., 2013). This appeared to be more intense for the two versions of the digital environments, as the differences in gamma activity were found to overall be larger.

Table 1. Statistically significant power differences ($p < .05$) for the three sets of environments, before (0) and after (1) the objects' position change (n.s.: non-significant)

Rh	Real 0	Real 1	3D 0	3D 1	2D 0	2D 1
θ	F8 O1	Fp1, Fp2 F7, F3, Fz, F4 T3, C3, Cz, C4, T4 T5, Pz O2	Fp1, Fp2 F7, F3, Fz, F4, F8 T3, C3, Cz, C4, T4 T5, P3, Pz, P4, T6 O1, O2	n.s.	Fp1, Fp2 F7, F3, Fz, F4 T3, C3, Cz, C4, T4 T5, P3, Pz, P4, T6 O1	O2
a	Fp1, Fp2 F7, F3, Fz, F4, F8 T3, C3, Cz, C4, T4 T5, P3, Pz, P4	O1, O2	Fp1, Fp2 F7, F3, Fz, F4, F8 T3, C3, Cz, C4, T4 T5, P3, Pz, P4, T6 O1, O2	n.s.	Fp1, Fp2 F7, F3, Fz, F4, F8 T3, C3, Cz, C4, T4 T5, P3, Pz, P4, T6 O1, O2	n.s.
β	Fp1, F7, F3, Fz, F4, F8 T3, C3, Cz, C4, T4 T5, Pz, P4, T6 O1	T3	Fp1, Fp2 F7, F3, Fz, F4, F8 T3, C3, Cz, C4, T4 T5, P3, Pz, P4, T6 O1, O2	n.s.	Fp1, Fp2 F7, F3, Fz, F4, T3, C3, Cz, C4 T5, P3, Pz, P4 O1, O2	F8 T6
γ	Fp1, Fp2 F7, F3, Fz, F4, F8 T3, C3, Cz, C4, T4 T5, P3, Pz, P4, T6 O1, O2	n.s.	Fp1, Fp2 F7, F3, Fz, F4, F8 T3, C3, Cz, C4, T4 T5, P3, Pz, P4, T6 O1, O2	n.s.	Fp1, Fp2 F7, F3, Fz, F4, F8 T3, C3, Cz, C4, T4 T5, P3, Pz, P4, T6 O1, O2	n.s.

Conclusions

The aim of this exploratory study was the investigation of the cognitive load and attentional demands in real and digital (3D stereoscopic and 2D) environments with the same content.

For this study’s needs, three sets of environments (a real, a 3D, and a 2D environment), with the same content, were developed. Each environment had a before (0) and after version (1), and 36 female undergraduate students were asked to observe the change of the position of three specific objects in each set. The participants’ brain activity was recorded through multiple EEGs. Theta, alpha, beta and gamma frequency bands were analyzed, compared for each environment (real, 3D, and 2D), and their before (0)/after (1) sets.

In regards to the study’s findings, the gamma activity, recorded during the observation of all three environments, supported that participants perceived the administered environments, their pertinent depicted objects, and the change of the objects’ position. Theta activity measurements revealed that participants’ also increased their selective attention for all three environments. Moreover, the cognitive load - associated with the performed task and the required mental effort (Young et al., 2014) - was noted to be higher in all environments before the change of the objects’ position. Similar observations were documented in the case of attentional demands, which were also higher in all the environments before the change. However, participants’ cognitive load appeared to reduce after the change, a finding attributed to the familiarity of the environments. Another noteworthy finding was the participants’ higher working memory load, working and spatial memory for the two digital environments (3D and 2D) before the change of the objects’ position. However, the opposite observation was noted for the real environment. Additionally, participants required higher visual attention for the real environment before the change but lower for the two digital environments after the change. These findings, although they could initially be considered as contradictory, require additional empirical evidence for their comprehensive interpretation, as few studies were available with specific findings regarding the relationship between visual attention and working memory (Scocchia et al., 2014).

As previously mentioned, mental effort and cognitive load are important parameters in learning environments’ design. The literature review revealed several studies with 3D stereoscopic learning environments. However, only a few studies reported on the differences between real, 2D, and 3D scenes, as far as cognitive load and attentional demands were concerned. Moreover, these parameters were usually reported to be measured with subjective methods (e.g., questionnaires), and less often by physiological measures, as the approach presented in this paper (i.e., use of EEG). Overall, few studies reported on brain activity, and pertinent differences in real, 3D and 2D scenes (Dan & Reiner, 2016). We believe that our study contributed to this innovative approach in the ICT research field, as we used electrophysiological monitoring methods (EEG), and obtained measurable and comparable biometric data (θ, α, β and γ brain rhythms). Overall, we suggest that empirical data, similar to the ones presented in this study, on cognitive load and attentional demands, can contribute to the design of improved learning environments.

Lastly and in terms of future research, we propose the utilization of additional signal processing techniques (such as coherence analysis), and the implementation of EEG dynamic models for a comprehensive and deeper “understanding of relationships between brain activity, experience, and behavior” (Onton, Delorme & Makeig, 2005).

References

Alexander, T., Conradi, J., & Winkelholz, C. (2003). Depth perception and visual after-effects at stereoscopic workbench displays. In J. Chen, B. Froehlich, B. Loftin, U. Neumann & H. Takemura (Eds.), *Proceedings of the IEEE Virtual Reality Conference 2003* (pp. 269-270). Los Alamitos: IEEE Press.

Arsenault, R., & Ware, C. (2004). The importance of stereo and eye-coupled perspective for eye-hand coordination in fish tank VR. *Presence: Teleoperators and Virtual Environments*, 13, 549-559.

Bastiaansen, M.C.M., & Hagoort, P. (2003). Event-induced theta responses as a window on the dynamics of memory. *Cortex*, 39(4-5), 967–992.

Dalgarno, B., & Lee, M. J. W. (2010). What are the learning affordances of 3-D virtual environments? *British Journal of Educational Technology*, 41(1), 10–32.

Dan, A., & Reiner, M. (2016). EEG-based cognitive load of processing events in 3D virtual worlds is lower than processing events in 2D displays. *International Journal of Psychophysiology*, https://doi.org/10.1016/j.ijpsycho.2016.08.013.

Donner, T. H., Siegel, M., Oostenveld, R., Fries, P., Bauer, M., & Engel, A. K. (2007). Population activity in the human dorsal pathway predicts the accuracy of visual motion detection. *Journal of Neurophysiology*, 98(1), 345-359.

Fink, A., Grabner, R.H., Neuper, C., & Neubauer, A.C. (2005). EEG alpha band dissociation with increasing task demands. *Cognitive Brain Research,* 24(2), 252-259.

Gruber, T., & Matthias, M. (2005). Oscillatory brain activity dissociates between associative stimulus content in a repetition priming task in the human EEG. *Cerebral Cortex,* 15(1), 109-116.

Gruber, T., Tsivilis, D., Giabbiconi, C. M., & Muller, M.M. (2008). Induced electroencephalogram oscillations during source memory: Familiarity is reflected in the gamma band, recollection in the theta band. *Journal of Cognitive Neuroscience*, 20, 1043-1053.

Huang, C.-F., & Liu, C.-J. (2012). An event-related potentials study of mental rotation in identifying chemical structural formulas. *International Journal of Environmental & Science Education*, 3(3), 37–54.

Holm, A., Lukander, K., Korpela, J., Sallinen, M., & Müller, K.M.I. (2009). Estimating brain load from the EEG. *The Scientific World Journal*, 9, 639–651.

Jacobs, G. D., Benson, H., & Friedman, R. (1996). Topographic EEG mapping of the relaxation response. *Biofeedback and Self-Regulation*, 21(2), 121-129.

Jansen, D.A., & Keller, M.L. (1998). Identifying the attentional demands perceived by elderly people. *Rehabilitation Nursing*, 23(1), 12-20.

Kesim, M., & Ozarslan, Y. (2012). Augmented reality in education: Current technologies and the potential for education. *Procedia - Social and Behavioral Sciences*, 47(222), 297–302.

Klimesch, W. (1999). EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Research Reviews*, 29, 169-195.

Maurer, U., Brem, S., Liechti, M., Maurizio, S., Michels, L., & Brandeis, D. (2015). Frontal midline theta reflects individual task performance in a working memory task. *Brain Topography*, 28(1), 127–134.

Mikropoulos, T. (2001). Brain activity on navigation in virtual environments. *Journal of Educational Computing Research*, 24(1), 1-12.

Moore, C., & Engel, S. A. (2001). Neural response to perception of volume in the lateral occipital complex. *Neuron*, 29(1), 277-286.

Onton, J., Delorme, A., & Makeig, S. (2005). Frontal midline EEG dynamics during working memory. *Neuroimage*, 15, 27(2), 341-56.

Paas, F., Tuovinen, J.E., Tabbers, H., & Van Gerven, P.W. (2003). Cognitive load measurement as a means to advance cognitive load theory. *Educational Psychologist*, 38(1), 63-71.

Paas, F., Tuovinen, J.E., Van Merrienboer, J.J., & Darabi, A.A. (2005). A motivational perspective on the relation between mental effort and performance: Optimizing learner involvement in instruction. *Educational Technology Research and Development*, 53(3), 25-34.

Ragan, E.D., Sowndararajan, A., Kopper, R., & Bowman, D.A. (2010). The effects of higher levels of immersion on procedure memorization performance and implications for educational virtual environments. *Presence: Teleoperators and Virtual Environments*, 19, 527-543.

Rouhinen, S., Panula, J., Palva, J.M., & Palva, S. (2013). Load dependence of β and γ oscillations predicts individual capacity of visual attention. *The Journal of Neuroscience*, 33(48), 19023–19033.

Salzman, M.C., Dede, C., Loftin, R.B., & Chen, J. (1999). A model for understanding how virtual reality aids complex conceptual learning. *Presence: Teleoperators and Virtual Environments*, 8, 293-316.

Scocchia, L., Valsecchi, M., Gegenfurtner, K.R., Triesch, J. (2014). Differential effects of visual attention and working memory on binocular rivalry. *Journal of Vision*, 14(5), 1-15.

Thompson, M., Thompson, J., & Wenqing, W. (2007). *Brodmann Areas (BA), 10-20 Sites, Primary Functions*. The ADD Centre & the Biofeedback Institute of Toronto. Retrieved 11 September 2017, from http://www.addcentre.com/Pages/professionaltraining.html.

Thut, G., Nietzel, A., Brandt, S. A., & Pascual-Leone, A. (2006). Alpha-band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *The Journal of Neuroscience,* 26(37), 9494-9502.

Trindade, J., Fiolhais, C., & Almeida, L. (2002). Science learning in virtual environments: a descriptive study. *British Journal of Educational Technology*, 33, 471-488.

Young, J. Q., Van Merrienboer, J., Durning, S., & Ten Cate, O. (2014). Cognitive Load Theory: Implications for medical education: AMEE Guide No. 86. *Medical Teacher*, 36(5), 371-384.

Van der Land, S., Schouten, A. P., Feldberg, F., van den Hooff, B., & Huysman, M. (2013). Lost in space? Cognitive fit and cognitive load in 3D virtual environments. *Computers in Human Behavior*, 29(3), 1054–1064.

Worden, M. S., Foxe, J. J., Wang, N., & Simpson, G. V. (2000). Anticipatory biasing of visuospatial attention indexed by retinotopically specific alpha band electroencephalography increases over occipital cortex. *The Journal of Neuroscience*, 20(6), RC63.

Wu, H., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education*, 88, 465-492.

Zacharis, G. K., Mikropoulos, T. A., & Priovolou, C. (2013). Stereoscopic perception of women in real and virtual environments: A study towards educational neuroscience. *Themes in Science & Technology Education*, 6(2), 109-120.

To cite this article: Zacharis, G. K., Mikropoulos, T. A., & Kalyvioti, K. (2016). Cognitive load and attentional demands during objects' position change in real and digital environments. *Themes in Science and Technology Education*, 9(2), 83-91.

URL: http://earthlab.uoi.gr/theste