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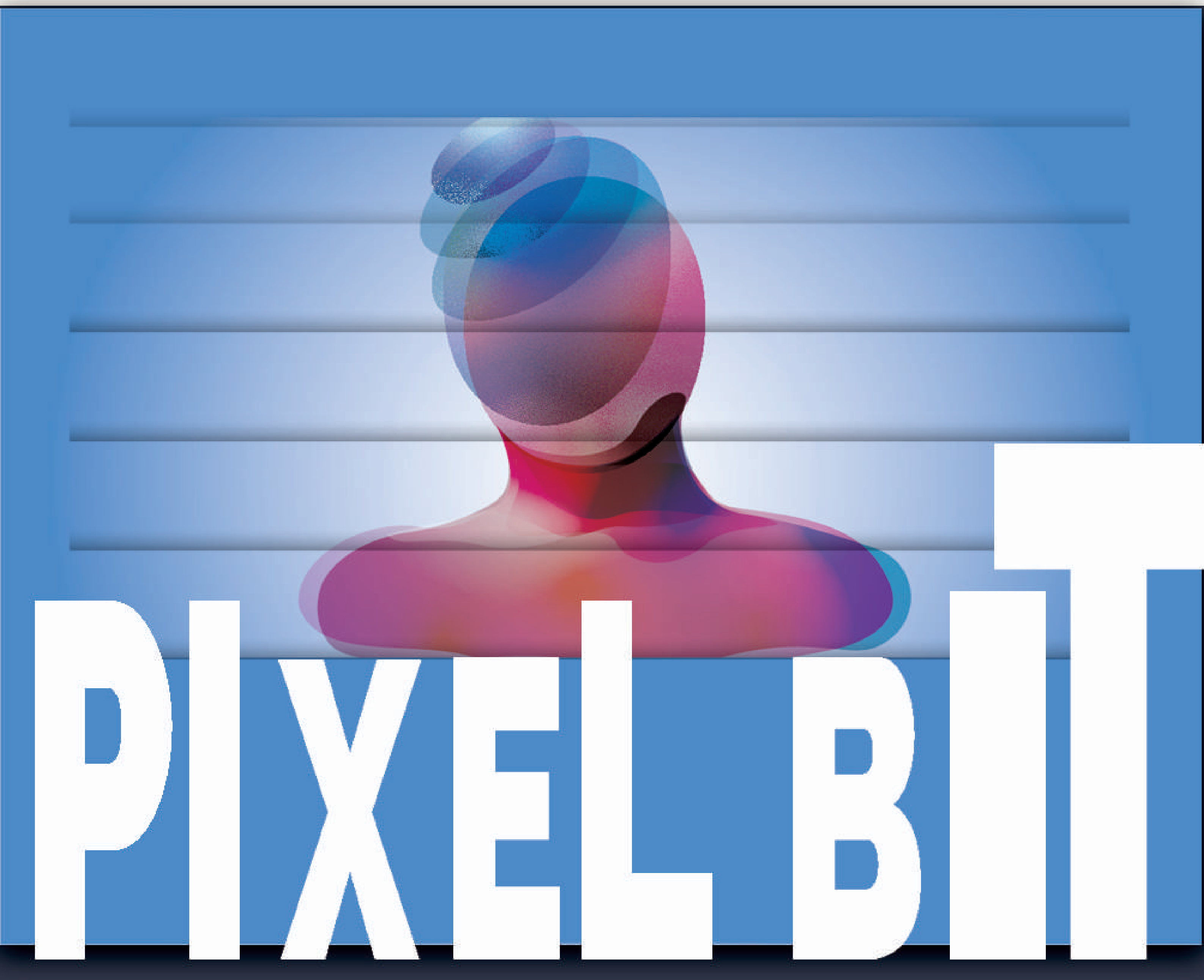

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REVISTA DE MEDIOS Y EDUCACIÓN
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Analysis of the Spatial Layout of Content in Augmented Reality Environments and its Effect on Users' Cognitive Load

Análisis de la Disposición Espacial de Contenido en entornos de Realidad Aumentada y su Efecto en la Carga Cognitiva de los Usuarios

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ABSTRACT
The spatial layout of information spaces in augmented reality (AR) environments plays a crucial role in modulating users' mental effort. This study aims to investigate how contiguity and discontiguity between physical objects and information spaces, both horizontally and vertically, affects cognitive load during interaction with procedural content. Four separate experiments were conducted, measuring pupil dilation and fixation duration as indicators of mental effort. These measures provide a comprehensive view on the influence of spatial layout. The findings are discussed within the framework of the existing literature, contrasting the results with previous studies and providing a basis for future research in the design of educational materials and learning environments. The results obtained across the four experiments show that the spatial arrangement of information in AR environments significantly affects participants' mental effort, as measured by pupil dilation and fixation duration. These measures are consistent with previous literature indicating that increased pupil dilation is an indicator of increased mental effort.

RESUMEN
La disposición espacial de los espacios de información en entornos de realidad aumentada (RA) juega un papel crucial en la modulación del esfuerzo mental de los usuarios. Este estudio tiene como objetivo investigar cómo la contigüidad y discontigüidad entre los objetos físicos y los espacios de información, tanto en el plano horizontal como en el vertical, afectan la carga cognitiva durante la interacción con contenido procedimental. Se realizaron cuatro experimentos diferenciados, midiendo la dilatación pupilar y la duración de las fijaciones como indicadores del esfuerzo mental. Estas medidas ofrecen una visión integral sobre la influencia de la disposición espacial. Los hallazgos se discuten dentro del marco de la literatura existente, contrastando los resultados obtenidos con estudios previos y proporcionando una base para futuras investigaciones en el diseño de materiales educativos y entornos de aprendizaje. Los resultados obtenidos a lo largo de los cuatro experimentos muestran que la disposición espacial de la información en entornos de RA afecta significativamente el esfuerzo mental de los participantes, medido a través de la dilatación pupilar y la duración de las fijaciones. Estas medidas son consistentes con literatura previa que indica que el aumento de la dilatación pupilar es un indicador de mayor esfuerzo mental.

KEYWORDS · PALABRAS CLAVES
Augmented Reality; Cognitive Load; Mental Effort; Emerging Technologies; Cognitive Processing; Instructional Design
Realidad Aumentada; carga cognitiva; esfuerzo mental; tecnologías emergentes; procesamiento cognitivo; diseño instruccional

1. Introduction

1.1 Augmented Reality in learning

Augmented reality (AR) is a technology that has been widely used in learning, especially in the learning of complex skills. Various studies have demonstrated their effectiveness in improving the spatial skills of engineering students (Guntur et al., 2020), the maintenance of military vehicles and equipment (Malta et al., 2023; Chow, 2021), as well as in the manufacturing industry (Doolani et al., 2020; Wang et al., 2022). Moreover, AR has proven to be a promising tool for training in maintenance and industrial assembly tasks, showing significant improvements in the performance of the operators who used it (Drouot et al., 2022; Danielsson et al., 2020). In the medical field, AR has facilitated training in surgical procedures, offering advantages for the development of basic and advanced skills (Tene et al., 2024; Singh et al., 2024), and allowing precise guidance during the initial stages of training (Evans et al., 2023).

In addition to the mentioned advantages, AR offers realistic haptic feedback, objective performance evaluation, and the possibility to document procedures for later review. However, a dependence on the information provided during training has been observed, which can negatively affect performance once the support is withdrawn (Hernán et al., 2021; Trávez, 2023). Therefore, careful design of AR experiences is recommended to effectively integrate visualization into the environment, minimizing interference with the task and maximizing the utility of visual information related to specific objects or spaces (Huang et al., 2015).

One of its main advantages lies in its ability to combine real and virtual objects in a learning environment, providing real-time information to the student during task execution (Garzón & Acevedo, 2019). The information provided through the graphical user interface (GUI) offers a practical guide for the student (Acosta et al., 2019; Czok et al., 2023; Anderson & Campbell, 2015; LeBel et al., 2017). The spatial organization of this information is important, as inadequate presentation can overload the student's cognitive processes during practice (Evans et al., 2017; Yang et al., 2023), primarily caused by working memory overload. Working memory is responsible for performing the cognitive processing of information received in real-time (Bertrand et al., 2017; Mayer, 2020; Rasmussen et al., 2016), and it is essential to ensure the usefulness of the information and the student's adequate performance.

1.2 Cognitive Load Theory in Learning

The Cognitive Load Theory (CLT) is a conceptual framework that seeks to describe how humans filter, process, store, and retrieve necessary information during learning processes. In this chapter, the TCC proposed by Sweller, which is based on the limited processing capacity of working memory, will be described. Baddeley (2003) defines Working Memory (WM) as a dedicated system that maintains and stores information in the short term, for periods between 15 and 30 seconds, and is the basis of human thought processes related to the conscious activity that a person develops. Based on the limited processing capacity of MT, Hanley (2016) proposes a Cognitive Load Theory, and later Mayer (2005) introduces the Cognitive Theory of Multimedia Learning (CTML) (Andrade-Lotero, 2012). These theories propose premises related to the use of limited cognitive resources and the limited capacity of a learner when faced with new information. According to the cognitive load theory

(CLT), applied to multimedia learning, the same learning material can induce different amounts of load on working memory (Sweller, 2020). This is due to the use of different presentation strategies, and to the fact that the different cognitive tasks required by these strategies can result in varying amounts of extraneous cognitive load. According to Brünker, free cognitive resources are defined by the difference between working memory capacity and total cognitive load. When this difference is minimal, cognitive overload occurs, which affects the learner's performance during training. Cheng et al. (2015) mention that extraneous cognitive load primarily arises from the design of defective materials or low-quality interfaces, which causes learners to consume additional cognitive resources in processing unrelated information during the learning activity. This ineffective cognitive load can be reduced through proper design and organization of the material.

1.3 Multimedia Principles for Learning

With the purpose of designing and organizing the material appropriately, Van Merriënboer and Kester (2014) propose a set of fourteen multimedia principles, among which the following stand out for procedural content: the Signaling Principle, which indicates that learning can be improved if the learner's attention is focused on the critical aspects of the learning task or the information presented; and the Spatial Contiguity Principle, which presents the largest effect size according to Sweller et al. (2019).

1.3.1 Spatial Contiguity

The concept of spatial contiguity associated with the multimedia principle states that students learn more effectively when corresponding words and images are presented close to each other on the page or screen, which minimizes the cognitive load required to integrate the information, according to Schroeder et al. (2018), and facilitates better retention and transfer of knowledge by allowing students to simultaneously retain visual information in working memory, as mentioned by Seraji et al. (2020) and Paek et al. (2017). Empirical studies have consistently demonstrated the benefits of spatial contiguity. For example, integrated designs in which text and diagrams are spatially aligned have shown significant improvements in learning outcomes compared to separate designs, as stated by Hidayat et al. (2018) and Craig et al. (2015). Moreover, according to Chikha et al. (2021), research has indicated that even incidental learning improves when spatial contiguity is maintained, suggesting that this principle aids in automatic cognitive processing. The effectiveness of the principle extends to various multimedia formats, including e-learning environments and virtual human interactions, where specific gestures for each element near the relevant content have been shown to improve retention, as Mayer mentions. (2008). Moreover, the studies that compared different multimedia presentations, such as the contiguity of text in the image with text linked to images through hyperlinks, did not find significant differences in learning gains, indicating that spatial contiguity can be maintained through various methods, according to Çeken and Taşkın. (2022). Similarly, according to Noetel et al. (2022), the principle of spatial contiguity can be used to direct visuospatial attention and improve cognitive processing by helping people focus and process visual information from specific locations in the environment, which aids them in understanding and interacting with the environment effectively. This type of attention is crucial for tasks that require precise visual focus, as it is achieved because the brain processes combined visual and auditory signals more effectively when they are spatially aligned, resulting in stronger brain responses and better performance in visual tasks.

The purpose of these experimental tests is to gather empirical evidence on the principle of spatial contiguity applied in an augmented reality environment. Considering aspects such as the inclusion of 3D material (object-information space), depth contiguity, and the relative position between 3D object-content. To achieve this, a set of four experimental tests was designed and executed: Spatial Contiguity of Visual Field, Spatial Contiguity in Depth, Contiguity with Horizontal Relative Position, and Contiguity with Vertical Relative Position. These tests were conducted with a group of 34 participants. An extended instructional material for knee anatomy was designed, visualized through Hololens2® augmented reality glasses. Eye tracking was used to capture data from the participants with SMI® glasses. The participant's pupil dilation data and fixation duration between the 3D object and the Information Space were processed in the BeGaze® software. The main results showed that, in relation to Mental Effort, it was found that the spatial contiguity of the field and the vertical relative position affect the mental effort of the participants. However, it cannot be confirmed that mental effort is affected by depth contiguity and relative horizontal position. These results, although they provide empirical evidence about the knowledge, show conditions in which the effect of applying the principle is still inconclusive. These data provide useful evidence for the design of learning materials for new interactive learning platforms such as augmented reality and allow for informed decision-making regarding the organization of information in the environment, with the aim of reducing cognitive load and mental effort. This information will undoubtedly help the designers of these environments to apply the principle of spatial contiguity in an informed manner.

2. Related Work

With the purpose of understanding knowledge, not only its effects but also how to leverage this principle, various investigations have been conducted. In two-dimensional environments, recent research evaluated the proximity between images and text in learning environments. For example, de Koning et al. (2020) evaluated that a greater spatial distance would increase cognitive load and hinder the learning of the fundamentals of electricity and electronic circuits. The study showed better learning outcomes, especially in recall, when shorter distances were applied. However, they mention the need for more research to establish the conditions under which this principle is applicable. Similarly, Beege et al. (2019) evaluated the influence of different proximities between related information, given that they consider it can promote or hinder learning. In two experiments, the spatial proximity between a pictorial presentation and text labels was manipulated. The results of the first experiment showed a significant effect of spatial proximity on learning performance. In experiment 2, the results showed greater retention and transfer at intermediate distances. These findings indicate that the transfer is optimal at an intermediate distance between the representation and the text. In this study, angular distances less than 10º were evaluated, as these are distances used in two-dimensional content to implement contiguity. Additionally, other conditions such as relative position are not evaluated, given that distance is considered a single spatial and two-dimensional component. Also, Cammeraat et al. (2020) evaluated spatial separation accompanied by the signaling principle in classical material for learning a clutch system, which used an image and text. In this experiment, only two levels of separation (close and distant) were evaluated, without specifying the separation values. Similarly, the separation is applied between the image and the text, the image taken as a single object, but not between the mentioned section of the image and the text. This could influence the application of the principle. The results did not show significant effects of spatial separation on learning or mental effort. As observed in the research, although there are favorable results from the application of spatial contiguity, these are not conclusive and require further investigation.

On the other hand, in spatial 3D environments that used augmented reality, Ens et al. (2014) studied the properties of screens for visualizing information in augmented reality. In an experiment, the impact on user performance was evaluated by varying the angular separation between screens (15º, 25º, 35º, 45º, and 55º) in tasks that required interaction with the content. It was found that both task time and selection accuracy degraded proportionally with the increase in angular distance, that is, the greater the angle, the longer the time and the greater the error. Additionally, at angles greater than 35º, the effect is significantly negative. Finally, in a subsequent experiment, an angular separation of 27.5º is used for the use of four displays in a mosaic. Müller et al. (2016) evaluated the connection by close spatial proximity in an augmented reality environment, in simple tasks of linking graphic information. The results showed that for the evaluated devices (HAr-Tablet, Video see-through, and Optical see-through), the time, subjective mental load, and mean error were lower. Additionally, the author proposes other integration mechanisms that could be effective for information relationships. Lei et al. (2019) studied performance in the execution of two tasks: a. High frequency of change and b. Low frequency of change. Three displays were used: the main one A, the secondary one B, and the support one C. It was identified that the distance between the displays is a factor that affects user performance. Despite not specifying a distance value, the separation was greater in a diagonal layout, followed by a horizontal layout, and smaller with a vertical layout. The results showed lower satisfaction for the moderate diagonal distance for high-frequency change tasks, but not for low-frequency tasks. However, the best performance in terms of task time and changeover time was for the vertical arrangement, as it had the shortest distance. In more recent studies, for example, in Bautista et al. (2022), augmented reality environments have leveraged spatial contiguity by closely integrating visual and textual elements, which has improved cognitive load management and knowledge retention. This principle has been particularly beneficial in procedural training, where augmented reality can display visual and auditory resources in a spatially contiguous manner, helping students associate information with specific tasks, according to Krüger and Bodemer. (2022). In experimental education, according to Zhang et al. (2020), multimedia environments based on augmented reality allow students to manipulate virtual objects in real-time, ensuring that the didactic content is spatially aligned with the experimental tasks, which enhances participation and learning outcomes. Moreover, the applications of augmented reality in the teaching of spatial geometry have shown that presenting 3D objects alongside related textual information helps students understand and visualize complex concepts better, thereby improving their spatial skills, as mentioned by Amir Alkodri et al. (2020). In general, according to Paek et al. (2017), the consistent application of the spatial contiguity principle in AR learning environments underscores its effectiveness in improving educational outcomes by reducing cognitive load and enhancing the association between instructional content and practical tasks (Craig et al., 2015; Putri et al., 2022; Solehatin et al., 2023).

All the reviewed studies measured the separation in angular form as seen from the observer. Studies showed that, for comparison tasks on conventional screens, negative behavior in performance or workload begins to appear at separations greater than 45º. No effect associated with head rotation was found. For tasks that involve interaction with the content, it was identified that the negative effect on task time and accuracy degrades proportionally as the separation increases. However, the effect increases significantly for separations greater than 35º. It was identified that a separation angle of 27º between displays could show better performance results for augmented reality environments. Likewise, in the reviewed studies, depth contiguity is not evaluated, despite involving a spatial user interface (3D); only visual field contiguity is assessed. The above does not allow us to understand the influence of the depth separation between contents. Likewise, the location used always showed horizontal contiguity in the field, but other positions of the content with respect to the image were not evaluated. On the other hand, the materials that were evaluated were generally two-dimensional materials such as images and text, but spatial origin objects like 3D models and integration were not evaluated: Text-model or image-model. This creates a possible limitation on the current state of knowledge of the principle and its applicability in space environments. Likewise, there is still no consensus on the effect on cognitive load, nor on the participant's performance when applying the principle. This reinforces what Krüger and Bodemer (2022) mention, suggesting the need for more studies related to this principle. This is because the results of the studies found are inconclusive regarding the reduction of cognitive load, as stated by Geng and Yamada (2020). Possibly, as Kapp hypothesizes, because it achieves a reduction in extrinsic cognitive load (Thees et al., 2020) that is more complex to distinguish with general tools. Likewise, few of the reviewed studies showed evaluations with objective tools, suggesting the need to use technologies like eye tracking (Suzuki et al., 2024).

2.1. Experiment 1: Field Spatial Contiguity

2.1.1. Materials and Methods

Hypothesis H1. With the purpose of understanding the mental effort behavior in participants using instructional content under Field Contiguity/Discontiguity conditions in an augmented reality environment, the study was proposed under the following hypothesis, H1: *The mental effort of the participant when the information space is contiguous to the object is different from when the information space is discontiguous.*

Experimental Design. The study proposed Field Contiguity as the independent variable, described in two categories: a. Contiguous: when the separation between the object and the information space is 30 degrees and b. Discontiguous: when the separation is 65 degrees. As the dependent variable, Mental Effort was taken, measured by Pupil Dilation and Fixation Duration in the AOI (area of interest). To collect this data, SMI® Eye Tracking glasses were used, and the data was processed with BeGaze 3.7 software. The group of participants consisted of 34 university students with an average age of 22.4 years, with little prior knowledge of the instructional topic.

For the execution of the study, the scene was designed for the learning of the surface anatomy of the patella and the patellar ligament of the knee. The scene uses a Prodelphus® knee simulator and the Information Spaces are visualized on Hololens2 glasses. Two levels of treatment were performed to locate the information space: a. Contiguous and b. Discontiguous, which were assigned randomly.

Procedure. The procedure began with the administration of the prior knowledge test. Once the low level of prior knowledge was verified, the reading and mechanical signing of the informed consent was carried out. Subsequently, the participant completed the tutorial to learn how to use the Hololens device and then took a five-minute break. Then, the participant was equipped with the SMI glasses and the eye-tracker was calibrated. Finally, the participant was fitted with the Hololens2 glasses and the treatment assigned by randomization was initiated.

Data Analysis. The eyetracking data were processed in the BeGaze 3.7 software. Subsequently, the statistical analyses were conducted using SPSS v26 software. Descriptive statistical analyses were conducted to understand the internal behavior of the data. Finally, the normality of the data was evaluated using the Shapiro-Wilk test and the homogeneity with the Levene's test, with a significance level of 5%. A comparison of means was performed using the paired T-student test for parametric data and the Wilcoxon Rank Test for non-parametric data, where the significance level was set at 5%, so $p<0.05$ values are considered statistically significant. Regarding the numbering system, we indicate that when the unit has a value of zero, it is not recorded, using a period instead of a comma, as recommended by APA. Example: "$p < .005$". The thousands will be separated by a comma and the decimals by a period: 1,532.27.3.

Ethical considerations: This set of experiments has been approved by the Committee on Ethics and Scientific Research of the Universidad Industrial de Santander (CEINCI) through Act No. October 8, 2021. The experiment required the instrumentation of the participants with measuring devices. However, it was not invasive and therefore classified as: No Risk. Additionally, the participants' information was coded to ensure the confidential handling of the data.

2.1.2. Results

2.1.2.1. Mental effort

Pupil Dilation: It was observed that the mean is higher for the Discontiguous treatment with a value of 0.16 with a SD (±0.28) mm compared to the Contiguous treatment whose mean was -0.03 SD (±0.13) mm. The normal distribution of the data was confirmed with the Shapiro-Wilk test (p-value = 0.22). The T-Student test was conducted, obtaining a (p-value= 0.001), showing significant differences in pupil dilation between the treatments. The effect size was calculated using Cohen's d, resulting in a large effect (d=0.87). The data suggest that mental effort is affected by the contiguity/discontiguity of the field between the object and the information space. Specifically, Field Discontiguity increases the mental effort in students, as observed in Table 1.

Table 1

Mental Effort Statistics: Pupil Dilation and Fixation Duration between AOIs for Field Contiguity

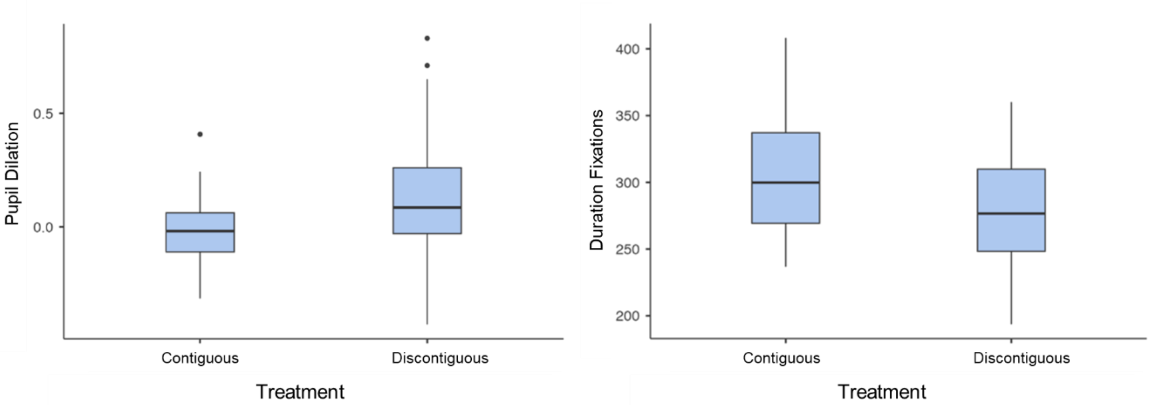
	Pupil Dilation (mm)				Duration of Fixations in the AOI (ms)			
	Treatment		**Contrast Test**	**Effect Size**	**Treatment**		**Contrast Test**	**Effect Size**
	Contiguous	Discontiguous	T-student	D-Cohen	Contiguous	Discontiguous	T-student	D-Cohen
Mean	-0,03	0,16	p-valor = 0,001	d=0,87	302,55	286,02	p-valor = 0,046	d=0,29
SD	0,13	0,28			54,6	57,6		

Source: The Author

Duration of Fixations in the AOI: The average Duration of Fixations for the Contiguous treatment is 302.55 ms with a SD (54.6), which is higher than the Discontiguous treatment that shows an average duration of 286.02 ms. With a DE (57,6 ms). The Shapiro-Wilk test (p-value = 0.413) was applied to verify the normality of the data. The T-Student test was conducted, obtaining a p-value of 0.046. The effect size was calculated using Cohen's d, resulting in a small effect (d=0.29). Therefore, the null hypothesis is rejected and the alternative hypothesis is accepted, indicating that there are differences in Fixation Duration between the treatments. The above indicates that the spatial proximity between visual elements affects the user's mental effort. In this case, the Discontiguous treatment generates a greater mental effort, evidenced by the duration of fixations. as observed in Figure 1.

Figure 1

Pupil Dilation and Fixation Duration, according to Field Contiguity Treatment



2.1.3. Discussion of Experiment 1

With the purpose of establishing significant differences in the mental effort of the participants, when the participant is exposed to the treatments of Contiguous and discontiguous information space in the field, Pupil Dilation and fixation duration in the AOI (information space) were measured.

In the evaluation of mental effort, through pupillary dilation, significant differences (p-value=0.001) were identified between the treatments. The analysis showed that for the Discontiguous treatment, pupil dilation is greater compared to the Contiguous treatment. The above could indicate the possible presence of mental effort in the participant, as Jarodzka et al. (2015) state that an increase in pupil dilation indicates greater mental effort, possibly generated by the Discontiguity of the Visual Field. Similarly, as shown by Rodemer et al. (2023) and Franklin et al. (2013) in the evaluation of mental effort in learning activities, an average pupil dilation value close to 0.2 indicates the presence of mental effort. That is possibly generated by the increase in the search for information required in the Discontiguous treatment. These results are consistent with the proposed hypothesis, as a difference in mental effort under the Field Contiguity/Discontiguity conditions was already expected. As Holsanova et al. (2009) also mention, the presence of Contiguity may encourage the processing of information present in the Object-Information Space set as a single source, which would reduce the participant's mental effort. These results show that when information is spatially separated, students require greater mental effort to process it, which can affect their concentration and learning efficiency. In contrast, information presented in a unified and close manner facilitates its processing and reduces cognitive load. The application of the principle of spatial contiguity allows students to understand and remember information more effectively, contributing to a more efficient learning process.

For the Duration of Fixations in the AOI, significant differences between the treatments were identified (p-value = 0.046). Identifying that the Duration of Fixations in the AOI for the Contiguous treatment was greater compared to the Discontiguous treatment. As indicated by Zu et al. (2018), the Duration of Fixations in the AOI is a measure of mental effort. That is, the participants maintained longer fixations on the AOI in the Contiguous treatment, while it was shorter for the Discontiguous treatment. This suggests a level of mental effort from the participants in the Discontiguous treatment, performing less deep processing, so it is possible that superficial processing occurs in the Discontiguous treatment. This is consistent with the related literature. For example, in Tao et al. (2019), they state in a recent review of eye-tracking measures that the mental task demand in flight and simulated driving tasks increased as fixation duration decreased. Similarly, Liu et al. (2022) found that fixation durations were shorter in tasks with high perceptual load. The findings are in line with the cognitive load theory, as, according to Zu et al. (2018), fixation duration can be considered a measure of mental effort that affects working memory, since the participant must store the instructions in working memory, which reduces their mental effort. These results imply that when information is presented contiguously, students maintain longer fixations on relevant areas, indicating deeper cognitive processing and greater mental effort dedicated to understanding the material. On the contrary, the discontiguous presentation reduces the duration of fixations, suggesting a more superficial and potentially less effective processing. This implies that organizing information in an integrated and accessible manner can facilitate students' concentration and comprehension, improving their ability to process and retain information.

2.2. Experiment 2: Spatial Contiguity of Depth

This characteristic is documented by Rashid et al. (2012) as depth contiguity, which is described as the difference in depth that exists between the object and the information space, measured with respect to the observer. Depth Contiguity is defined when the object and the information space are at the same depth with respect to the observer, and Depth Discontiguity when this relationship is broken, causing the information space to be at a different depth than the object. Therefore, the spatial contiguity of depth refers to the relationship between the physical separation of objects and their environment, and how this separation influences cognitive load.

2.2.1. Materials and Methods

Hypothesis H2. To understand the mental effort behavior of participants using instructional content under conditions of Depth Contiguity/Discontiguity in an augmented reality environment, the study was proposed under the following hypothesis, H2: *The mental effort of the participant when the information space is contiguous in depth to the object is different from when the information space is discontiguous in depth.*

Experimental design. The study proposed Depth Contiguity as the independent variable, described in two categories: a. Contiguous: when the information space is at the same depth as the linked object, measured with respect to the observer, and b. Discontiguous: when the information space is not at the same depth as the linked object, that is, the EI was placed 15 units closer to the observer. As the dependent variable, Mental Effort was taken, measured by Pupil Dilation and Fixation Duration in the AOI (area of interest). To collect this data, SMI® Eyetracking glasses were used, and the data was processed with BeGaze 3.7 software. The group of participants consisted of 34 university students with an average age of 24.3 years, with little prior knowledge of the instruction topic.

For the execution of the study, the scene was designed for the learning of surface and bone anatomy of the tibia and fibula. The scene uses a Prodelphus® knee simulator and the Information Spaces are visualized on Hololens2 glasses. Two levels of treatment were conducted to locate the information space: a. Contiguous in Depth and b. Discontiguous in Depth, which were assigned randomly

Procedure. The procedure followed was the same as that executed in Experiment 1 of Field Contiguity.

Data analysis. The same analysis as in experiment 1 was applied.

Ethical Considerations. The same as in Experiment 1.

2.2.2. Results

2.2.2.1. Mental effort

Pupil Dilation: The average pupil dilation is greater for the Discontiguous treatment with an average of (0.20 with a SD of 0.25) mm, compared to the Contiguous treatment whose average is (-0.05 with a SD of 0.18) mm. The normality of the data was verified with the Shapiro-Wilk test (p-value = 0.15). Subsequently, a paired T-Student test was conducted, obtaining a p-value of 0.000. A medium effect (d=0.68) was found, calculated using Cohen's

d. Therefore, the null hypothesis is rejected, and the alternative hypothesis is accepted, showing significant differences in pupil dilation between the Contiguity/Discontiguity depth treatments. Therefore, the data suggest that the Depth Contiguity/Discontiguity affects the mental effort in students. Specifically, the treatment of Depth Discontiguity increases mental effort, as observed in Table 2.

Table 2

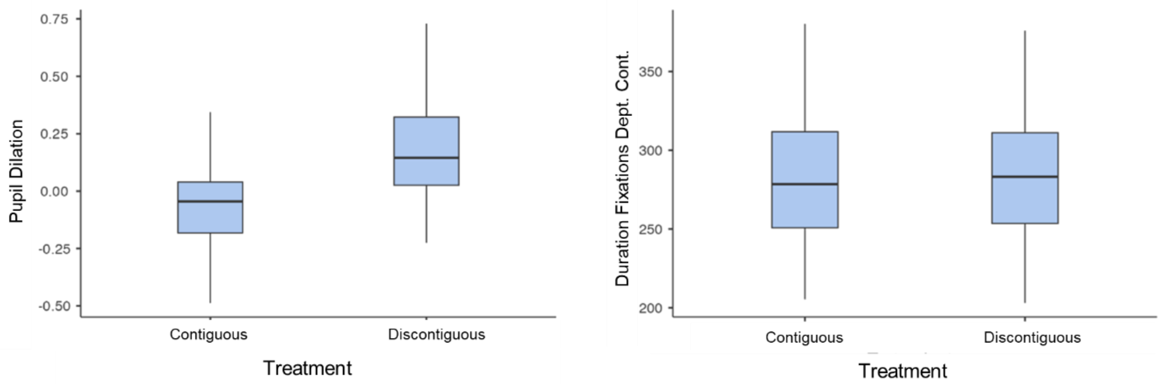
Mental Effort Statistics: Pupil dilation and Fixation Duration in the AOI for Depth Contiguity

	Pupil Dilation (mm)				**Duration of Fixations in the AOI (ms)**			
	Treatment		**Contrast Test**	**Effect Size**	**Treatment**		**Contrast Test**	**Effect Size**
	Contiguous	Discontiguous	T-student	D-Cohen	Contiguous	Discontiguous	T-student	D-Cohen
Mean	-0,05	0,2	p-valor = 0,000	0,68	279,48	284,37	p-valor = 0,204	-
SD	0,18	0,25			42,71	41,35		

Source: The Author

Figure 2

Pupil Dilation and Fixation Duration, according to Depth Contiguity Treatment



Duration of Fixations in the AOI: The average Fixation Duration for the Contiguous treatment (279.48 ms with a SD of 42.71) is very close to the average of the Discontiguous treatment. (284,37 ms con una DE 41,35). The normality of the data was verified with the Shapiro-Wilk test (p-value = 0.166). The T-Student test was conducted (p-value = 0.204). Therefore, the null hypothesis is accepted, and the alternative hypothesis is rejected, indicating that there are no significant differences between the treatments. That is to say, the duration of fixation on the AOI is indifferent for the treatments. Which suggests that Depth Contiguity might not affect the mental effort of students, as observed in Figure 2.

Finally, the data indicate that there is no conclusive information on the influence of Spatial Proximity (Discontiguity) in depth, which would allow us to affirm that the Discontiguous treatment can cause a greater mental effort in the participant.

2.2.3. Discussion of Experiment 2

To evaluate the hypothesis related to mental effort, Pupil Dilation and Fixation Duration in an AOI (Area of Interest) were analyzed. Significant differences were observed (p-value 0.000) between the treatments, with the Discontiguous treatment in depth being greater compared to the Contiguous treatment in depth. These differences showed a medium effect size (d=0.68). These results are in line with the expectations of the experiment, as a difference in pupil dilation between treatments was anticipated. Likewise, they coincide with the literature, especially with previous research, such as that proposed by Jarodzka et al. (2015), Rodemer et al. (2023), and Frankling et al. (2013). Additionally, Huckauf et al. (2010) report a higher cognitive cost for depth discontiguity. This is possibly caused by the fact that depth perception and the location of the stimulus relative to the user affect mental effort, especially due to the difference in depth between the object and the Information Space, which introduces the need for a constant adjustment of the participant's eye accommodation and convergence when using HMD devices like Hololens 2. Also, as mentioned by Pielage et al. (2022), the conflict between accommodation and vergence can cause possible alterations in the pupillary response. In this experiment, the Depth-Contiguous treatment had no depth difference between the object and the information space, which may have avoided the accommodation and vergence conflict mentioned by Huckauf; this could have had an impact on the reduction of cognitive cost. Conversely, the Discontiguous treatment may have promoted eye vergence accommodation during the activity, increasing pupil dilation. In other words, these results show that when augmented reality information is presented with depth discontiguity, students experience greater mental effort, reflected in increased pupil dilation. This suggests that the depth differences between the object and the information space increase cognitive load, possibly due to constant adjustments in accommodation and ocular convergence. When designing educational materials in augmented reality, it is essential to maintain depth contiguity between elements to reduce mental effort and promote more efficient and comfortable learning for students.

The measures of fixation duration in the AOI did not show significant differences between the treatments. (p-valor 0,204). Despite this, a longer fixation time was observed in the AOI when the Discontiguous treatment was presented. Despite what Guy et al. (2020) establish, the duration of fixation is modulated by the complexity of depth information processing, such as the distinction between simple and relative positional disparities; the latter require longer processing times due to the need to calculate multiple angular differences. Also, in visual search tasks, the duration of fixation increases with the heterogeneity of the distractors, the similarity between the target and the distractor, and the density of the stimuli, although their contribution to the search time varies with the complexity of the stimulus (Hans et al., 2014), a factor that did not vary between treatments, as the content was the same for both. Also, as indicated by Macramalia and Bridgeman (2009), depth cues such as the direction of lighting, shadows, and color balance are essential for accurate depth perception in two-dimensional images, and the mental effort required to process these cues can vary depending on the complexity of the visual task. In this experiment, no depth cues were included, therefore, it is possible that the lack of depth cues kept the effort level low, and thus, no difficulty was evident when the Discontiguous Depth treatment was used. However, it is clear that the Contiguity/Discontiguity of depth could be related to the perception of the depth of objects. As mentioned by Kemma et al. (2020), depth perception is crucial for controlling behavior in a three-dimensional world. However, contrary to how it was formulated in the hypothesis, research indicates that mental effort seems to influence depth perception (Takeuchi et al., 2011).

That is, as mentioned by Kalia et al. (2016), the presence of additional mental effort can affect depth perception, especially when augmented reality techniques are used to enhance visualization. That is, when the participant exerts high mental effort, they may incorrectly perceive the depth of the information space, leading to difficulties in proximity association. Additionally, it is possible that the separation distance used did not generate the Depth Discontiguity effect. Likewise, the position of the information space had minimal repositioning in the visual field between treatments, which might not represent a visual search task, but rather a physiological process of visual accommodation to associate the material shown in the information space. Then, the possible effects on mental effort could have originated in the process of accommodation and vergence, and not directly from a visual search. That is to say, the absence of depth cues and the minimal separation between elements could have kept the mental effort low in the discontiguous processing. This suggests that, to improve perception and reduce cognitive load, it is essential to incorporate depth cues and consider depth proximity when designing educational materials. By doing so, a correct spatial perception is facilitated, preventing additional mental effort from negatively affecting students' understanding and interaction with educational content.

2.3. Experiment 3: Contiguity - Relative Horizontal Position

2.3.1. Materials and Methods

Hypothesis H3. To understand the behavior of mental effort in participants using instructional content under conditions of Field and Depth Contiguity and Discontiguity, but with a horizontal relative position, the study was proposed under the following hypothesis: *The mental effort of the participants when the information space is to the right of the physical object is the same, whether the information space is contiguous or discontiguous to the object.*

Experimental Design H3. In this study, a univariate factorial design was applied with the independent variable defined as the contiguity of the information space located to the right of the object. Contiguity was evaluated at two levels: Contiguous, where the information space is aligned (in field and depth) with the object, and Discontiguous, where the information space is misaligned (in field and depth) with respect to the object. The dependent variable was Mental Effort, measured through Pupil Dilation and Fixation Duration in the Area of Interest (AOI). The data were recorded using SMI® Eye-tracking glasses and analyzed with BeGaze 3.7 software. The group of participants consisted of 34 university students with an average age of 21.8 years and with limited prior knowledge about the anatomy of the collateral ligaments of the knee, the subject of study. For the execution of the experiment, a scene was designed using the Prodelphus® knee simulator. The Information Spaces were visualized using Hololens2 glasses. Two treatment levels were randomly assigned for the location of the information space: Contiguous and Discontiguous. The experimental procedure and the statistical analyses applied were the same as those used in the first Field Contiguity experiment.

Hypothesis H4: The mental effort of the participants when the information space is to the left of the physical object is the same, whether the information space is contiguous or discontiguous to the object.

Experimental Design H4. In this study, a univariate factorial design with characteristics similar to the previous study was also applied. The independent variable was defined as the contiguity of the information space situated to the left of the object, evaluated at two levels: Contiguous and Discontiguous. The dependent variable was Mental Effort, analyzed through Pupil Dilation and Fixation Duration in the Area of Interest (AOI). The same SMI® Eye-tracking equipment and BeGaze 3.7 software were used for data collection and analysis.

The group of participants and the experimental conditions were identical to the previous study, where the contiguity of the information space to the right of the object was explored. This study was also designed to investigate the anatomy of the collateral ligaments of the knee using the Prodelphus® simulator and Hololens2 glasses for the visualization of Information Spaces. The treatment levels (Contiguous and Discontiguous) were randomly assigned, and the same experimental procedures and statistical analyses as in the first Field Contiguity experiment were followed.

2.3.2. Results - Information Space to the Right of the Object

2.3.2.1. Mental effort

Pupil Dilation: The mean for pupillary dilation is higher for the Discontiguous treatment (0.16 with a SD of 0.6) mm, compared to the Contiguous treatment (-0.24 with a SD of 0.53). The normality of the data was verified with the Shapiro-Wilk test (p-value = 0.113). The T-Student test was conducted, and a p-value of 0.003 was obtained. Therefore, the null hypothesis is rejected and the alternative hypothesis is accepted, indicating that there are significant differences in pupil dilation between the treatments. Therefore, based on the data, it is possible to state that there are differences in the participants' pupil dilation when the information space is Discontiguous, specifically when it is located to the right of the object. The above could affect the mental effort of the participants.

Duration of Fixations in the AOI: The results showed an average for the Contiguous treatment (283 with a SD of 54.30) very close to the average of the Discontiguous treatment. (282 con una DE 40,8). In the Shapiro-Wilk test (p-value = 0.035), it was verified that the data does not meet the normality assumption. The Wilcoxon rank test was performed (p-value = 0.661). Therefore, the null hypothesis is accepted, and the alternative hypothesis is rejected, indicating that there are no significant differences in fixation duration between the treatments, as shown in Figure 3.

Table 3

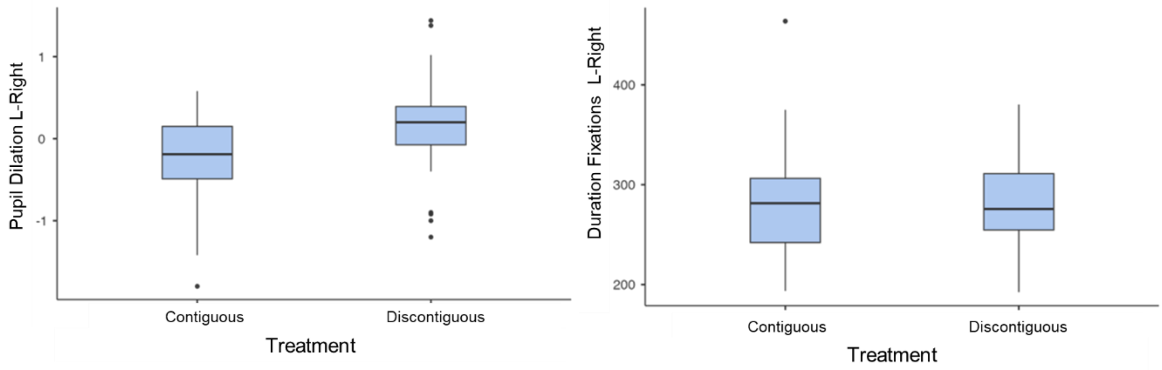
Mental Effort Statistics: Pupil dilation and Duration of Fixations in AOI (Information Space to the Right of the Object)

	Pupil Dilation (To the Right)					Duration Fixations (To the Right)				
	Treatment		**Normality Test**	**Contrast Test**	**Effect Size**	**Treatment**		**Normality Test**	**Contrast Test**	**Effect Size**
	Con t.	Discon .	Shapiro-Wilk	T-Student	D-Cohen	Cont .	Discon .	Shapiro-Wilk	Wilcoxon	C. Range
Mean	-0,24	0,16				283	282			
			p-valor =0,113	p-valor = 0,003	0,5			p-valor =0,035	p-valor = 0,661	-
SD	0,53	0,6				54,3	40,8			

Source: The Author

Figure 3

Pupil Dilation and Fixation Duration, according to treatment of Relative Horizontal Position to the Right



2.3.3. Results - Information Space to the Left of the Object

2.3.3.1. Mental effort

Pupil Dilation: The mean for pupillary dilation is higher for the Discontiguous treatment (0.28 with a SD of 0.73) mm, compared to the Contiguous treatment (0.06 with a SD of 0.43). The Shapiro-Wilk test was applied (p-value <0.001), finding that the data has a non-parametric behavior, as shown in Table 4. The Wilcoxon rank test was performed, yielding a p-value <0.011. Therefore, the null hypothesis is rejected and the alternative hypothesis is accepted, indicating that there are significant differences in pupil dilation between the treatments. Therefore, based on the data, it is possible to state that there are differences in the participants' pupil dilation when the information space is Discontiguous, when it is located to the left of the object.

Table 4

Mental Effort Statistics: Pupil Dilation and Fixation Duration in AOI (Information Space to the Left of the Object)

	Pupil Dilation (To the Left)					Duration Fixations (To the Left)				
	Treatment		**Normality Test**	**Contrast Test**	**Effect Size**	**Treatment**		**Normality Test**	**Contrast Test**	**Effect Size**
	Cont.	Discon.	Shapiro-Wilk	T-Student	D-Cohen	Cont.	Discon.	Shapiro-Wilk	Wilcoxon	C. Range
Mean	-0,06	0,28				271	284			
			p-valor <0,001	p-valor =0,011	0,5			p-valor = 0,003	p-valor =0,151	-
SD	0,43	0,73				51,7	70			

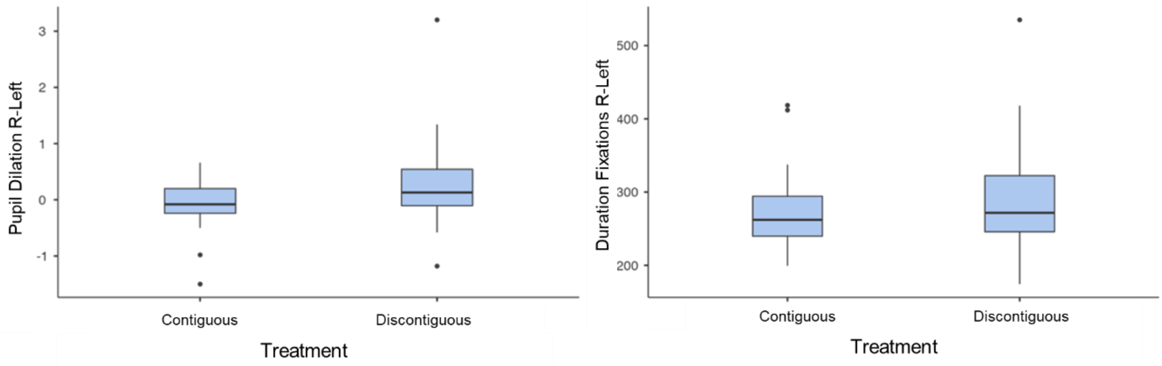
Source: The Author

Duration of Fixations in the AOI: The results showed an average for the Contiguous treatment (271 with a SD of 51.7) and for the Discontiguous treatment (284 con una DE 70). In the Shapiro-Wilk test (p-value = 0.005), it was verified that the data does not meet the normality assumption. The Wilcoxon rank test was performed (p-value= 0.151). Therefore, the null hypothesis is accepted and the alternative hypothesis is rejected, indicating that there are no significant differences in fixation duration between the treatments.

Based on the data, it can be concluded that mental effort is not affected by the horizontal relative position. That is to say, the relative horizontal position of the information space with respect to the object is indifferent in terms of mental effort, as evidenced in Figure 4.

Figure 4

Pupil Dilation and Fixation Duration, according to treatment of Relative Horizontal Position to the Left



2.3.4. Discussion of Experiment 3

In the present study, hypothesis H3 posited that the mental effort of the participants, measured through pupil dilation and the duration of fixations in the area of interest (AOI), does not vary significantly when the information space is located to the right of the object, regardless of whether the space is contiguous or non-contiguous to the object. The results showed that pupil dilation was significantly greater in the discontiguous condition (0.16 mm with a SD of 0.6) compared to the contiguous condition (-0.24 mm with a SD of 0.53), demonstrating significant differences with a p-value of 0.003. This suggests that spatial contiguity influences cognitive load, increasing mental effort when the information space is discontiguous to the object. According to Stoltmann et al. (2020), this response may be due to a natural inclination to conceptualize larger objects or quantities to the right, which could increase the cognitive load when trying to process discontiguous information in this position. On the other hand, no significant differences were observed in the duration of fixations in the AOI between the contiguous condition (283 ms with a SD of 54.30) and the discontiguous condition (282 ms with a SD of 40.8), with a p-value of 0.661 in the Wilcoxon rank test. This suggests that, while pupil dilation varies with contiguity, the duration of fixations is not similarly affected, possibly due to the specific nature of the task and how visual attention is distributed. These findings imply that mental effort may be generated possibly when the material is located to the right, but only when it is discogtinuous, that is, separated in depth and field of vision. The above implies that if the information space is to the right of the physical object, it will only generate mental effort under conditions of discontiguity. This means that such information spaces can be located to the right of the object in a contiguous manner to reduce the cognitive load resulting from information search.

For hypothesis H4, it was proposed that the mental effort of the participants does not vary significantly when the information space is located to the left of the object, regardless of whether the space is contiguous or non-contiguous to the object. The results indicated that pupil dilation was significantly greater in the discontiguous condition (0.28 mm with a SD of 0.73) compared to the contiguous condition (0.06 mm with a SD of 0.43), with a p-value of 0.011. This again shows that spatial discontiguity increases cognitive load. As Barnas and Greenberg (2019) and De De Nooijer et al. (2013) mention, cultural factors such as the directionality of written language can modulate these spatial preferences and reduce cognitive load by aligning educational materials with these natural biases. In terms of fixation duration in the AOI, no significant differences were found between the contiguous condition (271 ms with a SD of 51.7) and the non-contiguous condition (284 ms with a SD of 70), with a p-value of 0.151 in the Wilcoxon rank test. This reinforces the observation that pupil dilation is a more sensitive measure for detecting variations in mental effort under the evaluated contiguity conditions. These findings imply that presenting the information to the left of the object only affects cognitive load under conditions of discontiguity. That is to say, placing information spaces to the left of objects does not affect cognitive load.

The findings of the present study are consistent with the existing literature. Stolmann et al. (2020) suggest that natural spatial conceptualization influences cognitive load, which is reflected in the observed differences in pupil dilation. Furthermore, Barnas and Greenberg (2019) and De Nooijer et al. (2013) highlight the importance of aligning educational materials with spatial and cultural biases to optimize cognitive load and processing efficiency. In learning environments, the arrangement of information can play a crucial role in cognitive load, as noted by Zacharis et al. (2016), who state that cognitive load is higher in digital environments (2D and 3D) compared to real-world environments. This could explain why, in this study, discontiguity significantly affected pupil dilation, an indicator of mental effort. These results support what Tang et al. (2016) mentioned, who state that although the presentation modality does not significantly affect cognitive load, it does influence learning effectiveness, highlighting the relevance of how spatial information is presented. Additionally, Einhauser et al. (2020) highlight that spatial factors, such as the height and depth of stimuli, affect temporal perception and can influence information processing.

2.4. Experiment 4: Contiguity - Relative Vertical Position

2.4.1. Materials and methods

Hypothesis H5. To understand the behavior of mental effort in participants using instructional content under conditions of Field Contiguity and Discontiguity of Depth, but with vertical relative position (above or below the physical object), the study was proposed under the following hypothesis: *The mental effort of the participants when the information space is above the physical object is the same, whether the information space is contiguous or discontiguous to the object.*

Experimental design H5: In this study, a univariate factorial design was applied with the independent variable defined as the contiguity of the information space located above the object. Contiguity was evaluated at two levels: Contiguous, where the information space is aligned (in field and depth) with the object, and Discontiguous, where the information space is misaligned (in field and depth) with respect to the object. The dependent variable was Mental Effort, measured through Pupil Dilation and Fixation Duration in the Area of Interest (AOI). The data were recorded using SMI® Eye-tracking glasses and analyzed with BeGaze 3.7 software. The group of participants consisted of 34 university students with an average age of 21.8 years and with limited prior knowledge about the anatomy of the ACL and PCL ligaments of the knee, the subject of study. For the execution of the experiment, a scene was designed using the Prodelphus® knee simulator. The Information Spaces were visualized using Hololens2 glasses. Two treatment levels were randomly assigned for the location of the information space: Contiguous and Discontiguous. The experimental procedure and the statistical analyses applied were the same as those used in the first Field Contiguity experiment.

Hypothesis H6: *The mental effort of the participants when the information space is below the physical object is the same, whether the information space is contiguous or non-contiguous to the object.*

Experimental design H6: In this study, a univariate factorial design with characteristics similar to the previous study was also applied. The independent variable was defined as the contiguity of the information space located to the left of the object, evaluated at two levels: Contiguous and Discontiguous. The dependent variable was Mental Effort, analyzed through Pupil Dilation and Fixation Duration in the Area of Interest (AOI). The same SMI® Eye-tracking equipment and BeGaze 3.7 software were used for data collection and analysis.

The group of participants and the experimental conditions were identical to the previous study, where the contiguity of the information space to the right of the object was explored. This study was also designed to investigate the anatomy of the ACL and PCL ligaments of the knee using the Prodelphus® simulator and Hololens2 glasses for the visualization of Information Spaces. The treatment levels were assigned randomly, and the same experimental procedures and statistical analyses were followed as in the first experiment of Field Contiguity 1.

2.4.2. Results - Position Above the Object

2.4.2.1. Mental effort

Pupil dilation: It is observed that the mean of Pupil Dilation is greater for the discontiguous treatment (0.33 with a SD of 0.52) mm, compared to the Contiguous treatment (-0.02 with a SD of 0.51) mm. The normality of the data was evaluated using the Shapiro-Wilk test (p-value = 0.037), finding the non-parametric behavior of the data. The Wilcoxon rank test was conducted, yielding a p-value of 0.020. The effect size is medium (d=0.47) calculated using the biserial rank correlation. Therefore, the null hypothesis is rejected and the alternative hypothesis is accepted, indicating that there are significant differences between the treatments. Therefore, it is possible to assert that contiguity affects mental effort measured by pupil dilation. Specifically when the Information space is located above the object.

Duration of Fixations in the AOI: The average fixation duration in the Discontiguous treatment (309 with a SD of 91.9) ms was higher than the average in the Contiguous treatment (296 with a SD of 76) ms. The normality of the data was verified using the Shapiro-Wilk test (p-value = 0.661). The T-Student test was conducted, obtaining a p-value of 0.449. Therefore, the null hypothesis is accepted and the alternative hypothesis is rejected, indicating that there are no significant differences between the fixation durations of the treatments. Therefore, the data suggest that the duration of fixations is not affected by contiguity or discontiguity when the information space is above the object. That is, the duration of the fixation is the same when the information space is contiguous compared to when it is discontiguous, above the object, as can be evidenced in Figure 5.

Table 5

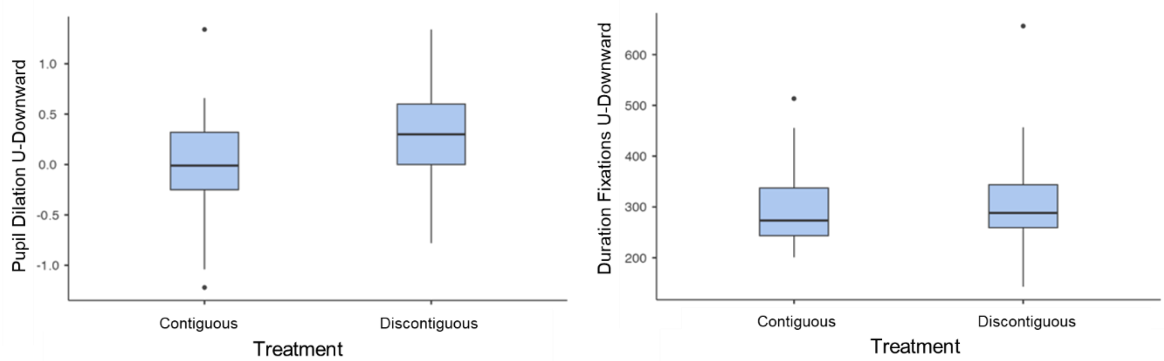
Mental Effort Statistics: Pupil dilation and Duration of Fixations in AOI. Information Space Above the Object

	Pupil Dilation (Up the object)					Duration Fixations (Up the object)				
	Treatment		**Normality Test**	**Contrast Test**	**Effect Size**	**Treatment**		**Normality Test**	**Contrast Test**	**Effect Size**
	Cont.	Discon.	Shapiro-Wilk	Wilcoxon	C. Range	Cont.	Discon.	Shapiro-Wilk	T-Student	D-Cohen
Mean	-0,02	0,33				296	309			
			p-valor =0,037	p-valor = 0,020	0,47			p-valor =0,661	p-valor = 0,499	-
SD	0,51	0,52				76	91,9			

Source: The Author

Figure 5

Pupil Dilation and Fixation Duration, according to treatment of Relative Vertical Downward Position



2.4.3. Results - Position Below the Object

2.4.3.1. Mental effort

Pupil dilation: It is observed that the mean of Pupil Dilation is higher for the discontiguous treatment (0.62 with a SD of 1.01) mm, compared to the Contiguous treatment (0.10 with a SD of 0.48) mm. The normality of the data was evaluated using the Shapiro-Wilk test (p-value <0.001), finding the non-parametric behavior of the data. The Wilcoxon rank test was performed, yielding a p-value of 0.006. The effect size is medium (0.54) calculated using the biserial rank correlation. Therefore, the null hypothesis is rejected and the alternative hypothesis is accepted, indicating that there are significant differences between the treatments. Therefore, it is possible to assert that contiguity affects mental effort measured by pupil dilation. Specifically when the Information space is located below the object.

Table 6

Mental Effort Statistics: Pupil dilation and Duration of Fixations in AOI. Information Space Below the Object

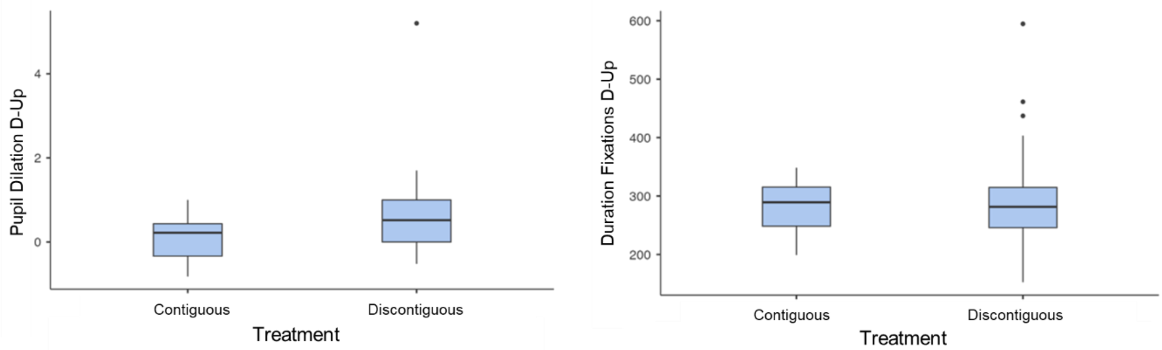
	Pupil Dilation (Down the object)					Duration Fixations (Down the object)				
	Treatment		**Normality Test**	**Contrast Test**	**Effect Size**	**Treatment**		**Normality Test**	**Contrast Test**	**Effect Size**
	Cont.	Discon.	Shapiro-Wilk	Wilcoxon	C. Range	Cont.	Discon.	Shapiro-Wilk	Wilcoxon	C. Range
Mean	0,1	0,62				281	290			
			p-valor <0,001	p-valor = 0,006	0,54			p-valor =0,047	p-valor = 0,840	-
SD	0,48	1,01				43,2	90,2			

Source: The Author

Duration of Fixations in the AOI: The average fixation duration in the Discontiguous treatment (290 with a SD of 90.2) ms was higher than the average in the Contiguous treatment (281 with a SD of 43.2) ms. The normality of the data was evaluated using the Shapiro-Wilk test (p-value = 0.047), finding a non-parametric behavior. The Wilcoxon rank test was performed, obtaining a p-value of 0.840. Therefore, the null hypothesis is accepted and the alternative hypothesis is rejected, indicating that there are no significant differences in the duration of fixations between the treatments. Therefore, the data suggest that the duration of fixations is not affected by contiguity or discontiguity when the information space is below the object. That is to say, the duration of the fixation is the same when the information space is contiguous compared to when it is discontiguous, below the object, as can be evidenced in Figure 6.

Figure 6

Pupil Dilation and Fixation Duration, according to treatment of Relative Vertical Position Up



2.4.4. Discussion of Experiment 4

The present study examined how the contiguity and discontiguity of the information space, in relation to the vertical position (above or below the physical object), influence the mental effort of the participants. This mental effort was measured through pupil dilation and fixation duration. The findings provide a detailed understanding of the impact that the spatial arrangement of information has on cognitive effort, with important implications for the design of educational materials and the optimization of learning environments.

The results for hypothesis H5 revealed that pupil dilation was significantly greater in the discontiguous condition compared to the contiguous condition when the information space was located above the object (p-value = 0.020). This result suggests that the misalignment of the information space in the upper position increases mental effort. This finding is consistent with previous research indicating that spatial arrangement can affect cognitive load (Tang, 2023). According to Stoltmann (2021), people tend to conceptualize larger objects on the right and smaller ones on the left, but this study extends that understanding to vertical arrangement, demonstrating that vertical misalignment also increases cognitive effort. Regarding the duration of fixations in the AOI, no significant differences were observed between the contiguous and non-contiguous conditions (p-value = 0.449). This suggests that, although vertical misalignment affects pupil dilation, it does not significantly influence fixation duration. This finding is consistent with Nooijer's (2018) studies, which mention that the alignment of educational materials can reduce cognitive load, although the duration of fixations may not be as sensitive to these changes. These findings have some implications for the design of the AR scene. That the placement of information spaces above the object in a condition of discontiguity should be avoided, this restriction is fundamental to maintaining scene design while promoting the reduction of cognitive load.

For hypothesis H6, the results showed greater pupil dilation in the discontiguous condition compared to the contiguous condition when the information space was located below the object (p-value = 0.006). This finding reinforces the notion that discontiguity increases mental effort, regardless of whether the information is above or below the object. This increase in mental effort can be explained by the cognitive load theory, which posits that spatial arrangement can influence the efficiency of information processing (Barnas & Greenberg, 2019). Similarly to hypothesis H1, no significant differences were found in the duration of fixations on the AOI between the contiguous and non-contiguous conditions (p-value = 0.840). This suggests that the fixation duration variable remains constant, regardless of the vertical location of the information. According to Zacharis (2017), cognitive load and attention demands are higher in digital and three-dimensional environments, which could explain why fixation duration does not vary significantly with the vertical relative position of the information. This finding reaffirms the contiguity of the information space with respect to the object, whether above or below it. This proposes a guide for the spatial placement of information spaces in 3D.

These results have implications for the design of educational materials and the layout of learning environments. It is essential to consider the spatial arrangement of information to minimize students' mental effort. In contexts of digital learning and augmented reality, the contiguous alignment of information with objects of interest can facilitate information processing and improve learning efficiency, as Tang (2023) points out. Understanding how spatial arrangement affects cognitive load can guide educational material designers in creating more effective learning environments. Einhäuser et al. (2020) mention that the spatial arrangement of stimuli, including their height and depth, influences the perception of time and, therefore, the processing of information. Thus, these aspects must be carefully considered to optimize instructional design.

This study highlights the relevance of the spatial arrangement of information in the mental effort of the participants. The results show that the contiguity of the information space either above or below the object can significantly affect pupil dilation, an indicator of mental effort, while the duration of fixations remains constant. These findings provide a foundation for future research and practical applications in the design of educational environments and teaching materials.

3. General Discussion

The spatial arrangement of information spaces in augmented reality environments plays a crucial role in modulating users' mental effort. This study aimed to investigate how contiguity and discontiguity, between the physical object and the information spaces, both horizontally and vertically, affect cognitive load during interaction with procedural content. Through four differentiated experiments, pupil dilation and fixation duration were measured as indicators of mental effort, offering a comprehensive view on the influence of spatial arrangement. These findings are discussed within the framework of the existing literature, contrasting the results obtained with previous studies and providing a basis for future research in the design of educational materials and learning environments.

The results obtained across the four experiments show that the spatial arrangement, especially the discontiguity, between the object and the information in augmented reality environments significantly affects the mental effort of the participants, measured through pupil dilation and fixation duration. These measures are consistent with previous literature indicating that increased pupil dilation is an indicator of greater mental effort (Jarodzka et al., 2015; Huckauf et al., 2010; Pielage, 2020).

It was observed that pupil dilation was greater in the discontiguous treatment, which suggests a higher mental effort due to the need to integrate spatially dispersed information. This is consistent with the findings of Holsanova (2016) and Rodemer and Frankling, who state that spatial contiguity facilitates information processing by reducing cognitive load. Conversely, the duration of the fixations was longer in the contiguous treatment, suggesting a deeper processing of the information in this condition. This finding aligns with previous studies that indicate a longer fixation duration is associated with a higher cognitive load (Tao et al., 2019: Liu et al., 2022). Likewise, it is evident that the mental effort due to the field discontiguity, between the object and the information space, also appears in the relative Horizontal positions (Right and Left) and vertical (Up and Down). Again, it was found that pupil dilation was greater in the discontiguous condition, supporting the hypothesis that depth discontiguity increases mental effort due to the constant adjustments of accommodation and vergence required (Huckauf et al., 2010; Pielage, 2020). No significant differences were found, which may be due to the lack of variation in depth cues, such as shadows and color balance, that could have influenced the perception and processing of information (Macramalia, 2018).

Pupil dilation was greater under discontiguous conditions, both to the right and to the left of the object. This supports the notion that spatial discontiguity increases cognitive load, possibly influenced by cultural factors such as the directionality of written language (Barnas & Greenberg, 2019; de Nooijer et al., 2013). No significant differences were observed, which indicates that the duration of fixations may not be as sensitive to variations in contiguity in the horizontal position. A greater pupil dilation was observed in discontiguous conditions, both above and below the object, suggesting an increase in mental effort due to vertical misalignment (Stoltmann et al., 2020; Barnas & Greenberg, 2019). Again, no significant differences were found, which suggests that vertical alignment may not affect fixation duration as much as pupil dilation does.

4. Conclusion

The findings of this study confirm that the spatial arrangement of information in augmented reality environments significantly influences users' mental effort. Specifically, it was found that discontiguity, both in the visual field and in depth, increases cognitive load, evidenced by an increase in pupil dilation. These results are consistent with previous studies indicating that spatial misalignment increases cognitive load (Jarodzka et al., 2015; Rodemer et al., 2010) and extend this knowledge by incorporating the depth dimension in three-dimensional AR environments.

The practical implications of these results are significant for the improvement of virtual learning environments and the design of environments that use AR. By demonstrating that spatial contiguity in all dimensions, horizontal, vertical, and depth; reduces cognitive load, it is suggested that designers of AR educational materials should place the information space adjacent to the object of interest. This would facilitate mental integration and content association, optimizing learning and information retention for users. Moreover, these results provide concrete guidelines for the design of AR environments and interfaces that avoid cognitive load, which is crucial for the development of more effective simulators and learning environments. By applying these recommendations, the user experience can be improved, increasing the efficiency and effectiveness of augmented reality-based educational applications.

Finally, this study not only confirms the impact of spatial arrangement on cognitive load but also offers practical guidelines for the design of AR educational materials, thus contributing to the optimization of AR learning environments and the advancement of more effective simulator designs.

5. Limitations and future work

This study presents some limitations that must be considered. First, because pupillary signals can have many sources of confusion, a limitation of studies with pupillary data is that they cannot be interpreted in isolation. Lighting changes introduce noise in pupil diameter, affecting the final data, especially when cognitive factors are analyzed (Kret, 2019), despite the software used applying corrections for lighting variations. Hennessy (1976) states that changes in lighting can impact spatial accommodation in an augmented reality environment, similar to the change in the human eye's lens that affects the focus of objects. Emotion is also a variable that can influence pupil diameter as a measure of mental effort (Brunken et al., 2016). Moreover, the duration of the measurement period is crucial, as short-duration stimuli do not produce pupil dilations that indicate mental effort (Reid, 2018); therefore, multiple measures should be considered during the execution of the test. Usually, studies that use eye tracking collect multiple data captures with the same participant. For this study, a single capture was performed per participant, which could represent a limitation. The findings of the study are based on a specific context that involves the visualization of anatomical instructions in an augmented reality space, which may not be generalizable to other themes or types of educational content.

Future research should consider some contexts to validate these results. It is also recommended to explore other indicators of mental effort, or the use of subjective tools such as the NASA TLX test or the Klepsh test, to gain a more comprehensive understanding of the impact of spatial arrangement on cognitive load. Future research could also benefit from longitudinal studies that evaluate the effect of contiguity on learning and long-term retention.

Author´s Contribution

Conceptualization, L. E. B., F. M., and G. P.; data curation, L. E. B.; formal analysis, L. E. B.; funding acquisition, L. E. B. and G. P.; investigation, L. E. B. and F. M.; methodology, L. E. B., G. P., and F. M.; project administration, L. E. B.; resources, L. E. B. and G. P.; software, L. E. B.; supervision, L. E. B. and G. P.; validation, L. E. B.; visualization, L. E. B.; writing—original draft preparation, L. E. B. and F. M.; writing—review and editing, L. E. B. and F. M.

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