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PAPER

Integrating EEG Analysis into Game-Based Learning: A Pilot Study on Memory Encoding and Learner Perceptions in Digital Educational Escape Games

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ABSTRACT

In the game-based learning (GBL) literature, it is widely accepted that digital educational escape games (DEEG) contribute to increased academic performance, improved motivation, and increase in learner engagement. However, while these results are empirically well documented, there is a lack of insights into the cognitive and neural processes behind the reported results. This pilot study attempts to address this issue through an interdisciplinary research design. It includes both GBL and educational neuroscience (EN) to understand which mental processes are involved when interacting with a DEEG. The study engaged 23 adults, divided into three experimental groups. During their interactions in the different experimental conditions, changes in their brain waves were recorded via the use of an electroencephalogram (EEG). Specific attention was given to the neural markers of memory encoding/retrieval (hippocampal theta waves) as well as concentration (low beta waves) and the participants' perceived usefulness of the activity (frontal alpha wave asymmetry). The study showed a significant increase in memory encoding/retrieval among the participants interacting with the DEEG. This increase was found to be linked to the participants' perceived usefulness of the activity.

KEYWORDS

game-based learning (GBL), educational neuroscience (EN), digital educational escape games (DEEG), electroencephalography (EEG), memory encoding, learner perceptions

1 INTRODUCTION

Within the learning sciences, it is widely accepted that classroom activities designed to get students to participate actively in the learning process produce better learning. Likewise, several experiments within the domain of game-based learning (GBL) have reported that students who were subjected to learning with digital games recorded significant improvements in the fields of subject understanding, diligence,

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and motivation [1]. Similarly, digital educational escape games (DEEG) have gained attention in recent years among researchers and educators who use them to explore different educational contexts [2]. In a systematic review of 45 peer-reviewed articles, conference papers, and book chapters about the pedagogical potential of DEEGs, Makri and colleagues concluded that all of these studies reported increased academic performance, improved motivation, positive behaviors and feelings, as well as increased learner engagement. But although these studies document positive achievements in the domain of learning goals, they offer no insight into the mental processes involved in this type of learning compared to other forms of learning.

This gap is increasingly being addressed by the scientific community of educational neuroscience (EN) that seeks to bring educational psychology and neuroscience together [3].

And even though this emerging field is not without its critics [4], [5], findings achieved with these new methodologies do suggest that there is a direct link between education and neuroscience, bringing cognitive and neural processes together [3].

It is therefore the aim of this pilot study to expand on the existing findings of increased learning when using DEEGs. Through the use of educational neuroscience, the underlying mental processes involved when interacting with a DEEG will be explored. By investigating different learning environments through the lens of neural markers and their associated mental processes, we are bringing together cognitive and neural processes. According to Mareschal and colleagues., such a non-reductionist framework that holds details about the environment, the cognitive, and the neural levels is needed if we want to strive for a full account of learning [3].

1.1 Neural activity

The foundation of neural processes is found when information from our environment is absorbed through our sensory apparatus. The information moves through our brain in pools of neurons that are either activated or inhibited. These rhythms, or brain waves, are oscillations or repetitive patterns of neural activity. Depending on the speed of these oscillations or the wavelength of the rhythm, a frequency is emitted, which can be measured with the use of an electroencephalogram (EEG). Different frequencies favor different connections and neural computations [6]. An example of this is navigation or visual orientation in a novel environment. Here, an increase of brain waves in the frequency band of 4–8 Hz (theta waves) can be measured in the brain's hippocampal area. This neural marker, an increase in hippocampal theta waves, corresponds to the mental process of memory encoding or memory retrieval [7], [8]. Likewise, an increase in brain waves with a frequency of 8–12 Hz (alpha waves), occurring asymmetrically in the frontal cortex, is a neural marker corresponding to the mental process of either a positive or negative perception of an environmental event [9], [10]. Concentration is widely reported to create a neural marker where brain waves in the 12–30 Hz area (beta waves) are increasing [11], [12].

1.2 Research design

In an interdisciplinary research design, including both GBL and EN, this pilot study investigated the neural effects of the core game mechanics in a DEEG and compared them with two other digital learning activities. Specifically, the study focused on the game mechanic that involves visual orientation in a novel environment. Here, the user is decoding the learning environment, looking for hidden clues that in EN are known to increase memory encoding or memory retrieval. Such an increase can be registered with EEG measuring a heightened neural activity of hippocampal theta waves [7], [8]. Likewise, the study also focused on the widely accepted phenomenon that GBL is capable of increasing positive engagement [13]. In EN, such positive engagement with a technological artifact, here referred to as perceived usefulness [14], can be registered on EEG through a frontal asymmetry in the alpha band [10]. The study also investigated the mental process of concentration, which is widely reported to create a neural marker measurable through an increase of brain waves in the 12–30 Hz area (beta waves) [11], [12].

To measure these three markers, a research paradigm with an experimental group and two control groups was designed. Control group 1 (G1, n = 7) was asked to read a text from a computer screen. The experimental group (G2, n = 8) was asked to play a DEER. And the second control group (G3, n = 7) was asked to play a first-person shooter game (FPS). This ensured that the mental processes recorded from G2 could be compared to an everyday learning activity, in this case, the reading of a text. Likewise, the visual orientation in a 3D environment of a computer game, in this case the FPS "CS: GO," could be compared to visual orientation in the DEER.

In the first control group (G1), the chosen text did not fit entirely on the user's screen, which meant they had to use a mouse to scroll to the end of the text. This design was chosen to ensure that the participants in G1 also used mouse movements, similar to the participants in G2 and G3. Likewise, the text was in a non-native language for all participants (English), and the content was from a knowledge domain in which no participant had prior knowledge (the Jewish holiday of Hanukkah). This ensured that any native speaker or prior knowledge biases could be excluded.

For the purpose of comparing the DEER experimental group (G2) to the second control group (G3), a custom DEER was specifically built for this study. The main emphasis is on the controls as well as the in-game field of view. These were constructed to be exactly the same as those used in the game in G3. This design ensured that the core action of moving in a novel 3D environment was comparable, while the variable that was changed in G2 compared to G3 was the actual gameplay.

2 MEASURING MENTAL ACTIVITIES

A common way to measure mental processes in neuroscience is through time-locked activity or event-related potential (ERP). This method helps capture neural activity related to both sensory and cognitive processes. It relies on measuring the changes in voltage generated in the brain structures as a response to a specific event or stimulus [15].

However, due to the exploratory nature of this pilot study, a broader approach was chosen. Contrary to the single stimulus used in ERP, continuous recordings of task-independent activities were applied. This allows the collection of mental processes from activities with different parameters. It is acknowledged that such a task-independent activity could lead to a weaker result, which might not be directly quantifiable. Should a positive result be found in such a broad data set, a follow-up study with a targeted, task-specific design should be able to produce a stronger and quantifiable result.

For this reason, a stimulus-independent protocol was designed in which all participants were recorded twice. The first recording (R1) captured the mental processes in an identical activity for all participants across the different experimental conditions. The second recording (R2) captured activities specific to their assigned groups (G1, G2, or G3). This established a comparable baseline for all participants with R1, from which any deviations in the three activities (R2) could be measured.

2.1 Research questions

The primary question this study addresses is whether a DEEG can enhance memory encoding/retrieval in a task-independent activity. A secondary focus was on the correlations between memory encoding/retrieval and the mental processes, concentration, and perceived usefulness.

3 METHODOLOGY

Twenty-three healthy adults (nine women and 14 men) aged 22–60 (M = 35.8) participated in this study. Fourteen of them didn't play computer games, while nine were playing computer games on a regular basis at the time of the experiment. The participants were randomly divided into the three activities (G1, G2, and G3). The EEG recordings were conducted in a quiet room, free from external distractions. During the experiment, each participant was alone in the room with the researcher. During R1, the participants listened to two minutes of soothing music while looking at a pleasant image on a computer screen. Before starting the second recording (R2), the participants were given a minimum of instructions on how to maneuver during the game or how to scroll in the text with the mouse. They were given no task to fulfill during the activity, which lasted for three minutes.

The EEG headset used was the Emotiv Insight ver. 2.0, and the data used in this study were collected from the T7, T8, AF3, and AF4 electrodes placed in accordance with the international 10–20 standard. After recording the participants' brain wave activity in the Emotiv Pro software, it was exported to the. edf (European Data Format) file format. This made it possible to import raw EEG data into the EEGLab software package from the Swartz Center for Computational Neuroscience at the University of California. Using this software package with the raw EEG data made it possible to exclude any third-party software calculations and use a software environment that is well known for its academic validity. This excluded any close-source algorithmic biases in the results.

The data was cleaned for artifacts using a high-pass filter, referencing the data through a computational average, and in the end, the ICA (Decompose Data) method in EEGLab was applied to the data. This removed interferences from muscles, eyes, and other artifacts. 1 dataset was excluded from the final analysis due to a large number of muscle artifacts.

4 RESULTS

To get an understanding of the mental process of memory encoding/retrieval the mean value of the hippocampal theta waves, measured in microVolts squared pr. hertz, in both the baseline (R1) and the activity (R2) was calculated for all three groups.

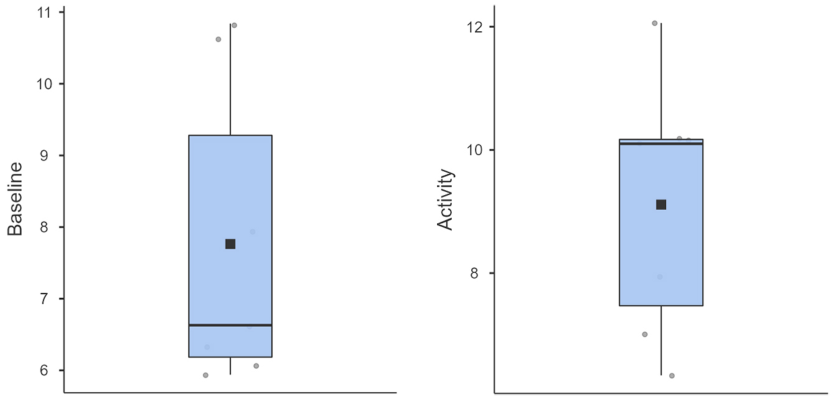

Fig. 1. G1 Hippocampal theta waves in baseline and when reading a text on a screen

In the first group (G1), the mean value of hippocampal theta waves was highest in the activity of reading a text on screen (M = 9.12, SD = 2.06), compared to the value of the baseline (M = 7.76, SD = 2.14). This showed a mean increase of 1.35 microvolts during the activity.

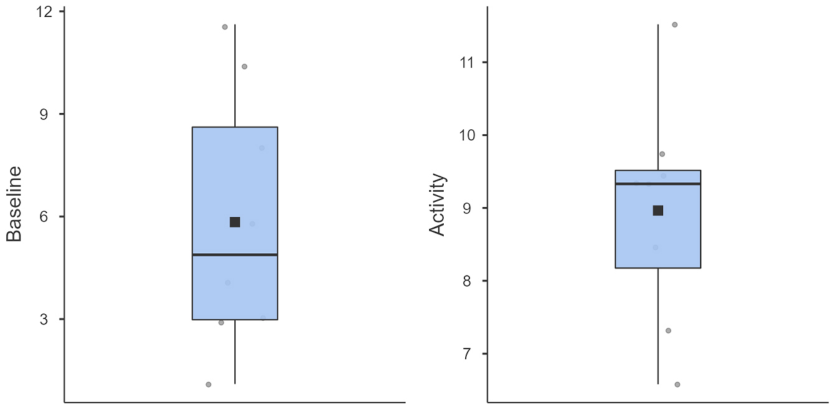

Fig. 2. G2 Hippocampal theta waves in baseline and when interacting with the DEER

In the second group (G2), the mean value of hippocampal theta waves was highest in the activity of interacting with the DEER (M = 8.96, SD = 1.52), compared to the value of the baseline (M = 5.84, SD = 3.80). This showed a mean increase of 3.12 microvolts during the activity.

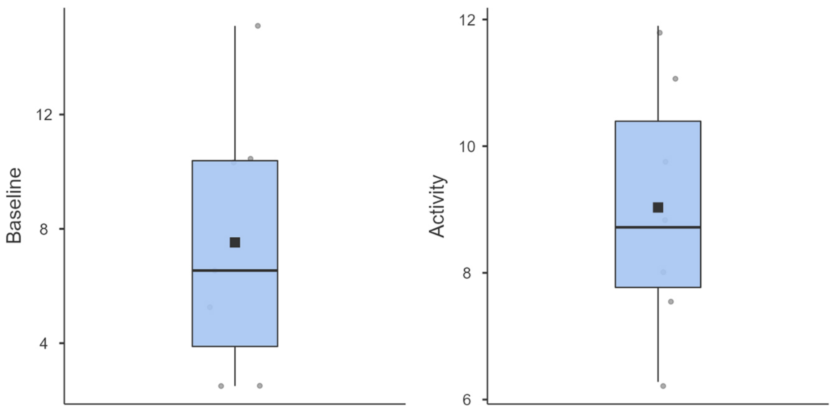

Fig. 3. G3 Hippocampal theta waves in baseline and interacting with FPS

In the third group (G3), the mean value of hippocampal theta waves was highest in the activity of interacting with a FPS (M = 9.03, SD = 2.00), compared to the value of the baseline (M = 7.53, SD = 4.66). This showed a mean increase of 1.50 microvolts during the activity.

All activities showed an increase in hippocampal theta waves during the activities (see Figures 1–3). This corresponds to the neural marker of memory encoding/retrieval.

The results showed that an increase in memory encoding/retrieval could be registered in all three activities. It also showed that the increase was significantly larger for users interacting with the DEEG. Compared to users in G1 that were reading a text, it was an increase of 1.31, and compared to users in G3 interacting with the 3D FPS game, it was an increase of 1.08.

4.1 Assessing the statistical validity

However, due to the low sample size, a paired samples t-test was chosen to assess the statistical validity of these results. The test was conducted at baseline. This was chosen to compare the result of the baseline and the result of the activity. The alternative hypothesis (H_a) proposed was that the mean of the baseline would be less than the mean of the activity.

Table 1. Paired samples t-test of G1

	t-Value	df	p
Baseline Activity Student's *t*	–1.14	6.00	**0.149**

Note: H_a $\mu_{\text{Measure 1 – Measure 2}} < 0$, *p < .05, **p < .01, ***p < .001.

The results from the paired samples t-test of G1 indicated no statistical significance between the mean of the baseline and the mean of the activity.

Table 2. Paired samples t-test of G2

	t-Value	df	p
Baseline Activity Student's *t*	–2.02	7.00	**0.042***

Note: H_a $\mu_{\text{Measure 1 – Measure 2}} < 0$, *p < .05, **p < .01, ***p < .001.

The results from the paired samples t-test of G2 did indicate a statistically significant difference between the mean of the baseline and the mean of the activity, thereby supporting the alternative hypothesis (H_a).

Table 3. Paired samples t-test of G3

	t-Value	df	p
Baseline Activity Student's *t*	–0.661	6.00	0.276

Note: H_a $\mu_{\text{Measure 1 – Measure 2}} < 0$, *p < .05, **p < .01, ***p < .001.

The results from the paired samples t-test of G3 indicated no statistical significance between the mean of the baseline and the mean of the activity.

In summary, the results from the t-tests (refer to Tables 1–3) indicate that interacting with a DEER has a significant effect on memory encoding/retrieval, as seen by the participants in Group 2 (refer to Table 2). In contrast, the two control groups (refer to Tables 1 and 3) didn't show any statistically significant differences between baseline and their respective activities. This supports the hypothesis that memory encoding/retrieval increases during interaction with a DEER.

4.2 Exploring correlations

To get a better understanding of the mental processes associated with the detected increase of memory encoding/retrieval, it was decided to explore their correlations with perceived usefulness and concentration. Similar to the data that formed the basis for calculations of memory encoding/retrieval, the data for concentration and perceived usefulness were calculated as mean values between the baseline (R1) and the activity (R2) for all three groups (G1–G3) before the data were added to a Pearson's correlation matrix.

For G1, a positive correlation between concentration and memory encoding/retrieval was found ($r = 0.662$, $p = 0.105$). And a positive correlation was also found between concentration and perceived usefulness ($r = 0.693$, $p = 0.085$). This suggests a moderate positive relationship between concentration and the other variables, although it is not statistically significant.

For G2, a weak, non-significant positive correlation between concentration and memory encoding/retrieval was found ($r = 0.275$, $p = 0.551$). While a moderate, non-significant positive correlation between concentration and perceived usefulness ($r = 0.602$, $p = 0.153$) was found. However, G2 also displayed a strong and statistically significant positive correlation between memory encoding/retrieval and perceived usefulness ($r = 0.870$, $p = 0.005$). Indicating that higher perceived usefulness was associated with better memory encoding. This suggests that perceived usefulness, as opposed to concentration, may play a key role in enhancing memory encoding/retrieval for this second group interacting with the DEEG.

For group 3 (G3), a weak, non-significant positive correlation between concentration and memory encoding/retrieval was found ($r = 0.348$, $p = 0.444$). And a significant negative correlation was found between concentration and perceived usefulness ($r = -0.797$, $p = 0.032$), suggesting that higher levels of concentration were associated with lower perceived usefulness. The correlation between memory encoding/retrieval and perceived usefulness was negative and non-significant ($r = -0.113$, $p = 0.810$).

This data shows a significant correlation between memory encoding/retrieval and perceived usefulness when users interact with a DEER (G2). Concentration and perceived usefulness seem to have a significant negative correlation when users interact with a FPS (G3). No significant correlations could be found between any of the three mental activities when the users were reading text on screen (G1).

5 DISCUSSION

In summary, the methodology used in this exploratory pilot study was able to capture traces of subtle neural markers for the mental activities of memory encoding/retrieval, perceived usefulness, and concentration. Furthermore, the results of a mean increase in hippocampal theta waves of 3.12 microvolts found in the DEER condition indicate that such a learning environment is plausible to have a positive impact on memory encoding/retrieval. The condition also displayed a positive correlation between perceived usefulness and memory encoding/retrieval, suggesting that a learner's perception of an activity's value might increase the mental activity of memory encoding/retrieval.

These findings underline the potential of integrating EEG analysis when evaluating the effectiveness of GBL activities. The approach could offer a richer, non-reductionist view of the learning process by bridging low-level neural measures with cognitive processes. And provide a methodology for a more holistic view of the learning process, thereby addressing concerns about the oversimplification of learning dynamics as highlighted by Ochoa [16].

However, the small sample size and the use of a 5-channel EEG device pose two limitations that can affect the generalizability of the findings. Additionally, the choice to use task-independent activities, while chosen to facilitate a broader data set, delivered a weaker result compared to the neural responses that a well-defined, task-specific learning activity might have provided. Future studies might benefit from extending the EN approach by adding more sophisticated equipment. For instance, compared to the existing configuration, employing EEG headsets with 32 or 64 channels may offer a more nuanced spatial mapping of the neural activity. A further level of detail could be added by using fMRI, which may provide insights into the brain regions used during learning activities. Combining this with a larger sample size and a task-specific design, the methodological approach could help us gain a more nuanced understanding of how the learning environment influences mental processes and their influence on learning.

Nonetheless, since it is widely reported that the use of Educational Escape Games, and here also their digital versions, increases academic performance, improves motivation, positive behaviors and feelings, and learner engagement [1], [2], and this study demonstrated a link between perceived usefulness and a significant increase in memory activity, it might suggest that students would be more likely to encode or retrieve information from the DEEG, compared to, for instance, reading. The gameplay of DEEG might therefore be a positive and engaging way of reinforcing previously taught material, helping students to better encode and retain information. A new research direction could be pursued in further studies with this interdisciplinary research design.

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