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An EEG study to understand semantic and episodic memory retrieval in creative processes

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Abstract

This study aimed to identify and compare the EEG activities associated with semantic and episodic memory retrieval during creative processes. Episodic and semantic memory induction studies were conducted and EEG was used to collect data. The results showed that (i) Episodic and semantic memory retrieval are related to the frontal lobe area; (ii) Semantic memory retrieval is evoked more swiftly compared with episodic memory retrieval (ii) Prior to episodic memory retrieval, semantic memory retrieval is evoked first.

Keywords: EEG, design creativity, design cognition, semantic memory, episodic memory

1. Introduction

Creativity in design related to human's ability to coming up with novel and value ideas (Yin et al., 2023). Creativity is a process that involves generating new ideas by searching (Fink & Benedek, 2014), interacting with (Palmer, 2020) and associating (Benedek & Fink, 2019) existing memories. Memory thus is one of the fundamental elements of creativity (Beaty et al., 2017; Benedek & Fink, 2019; Yin et al., 2019, Childs et al., 2022). One example to support the key role of memory in creative design is that in a divergent thinking (DT) process, people tend to recall information related to the target design task before generating new ideas (Beaty et al., 2017). Therefore, it is important for designers and researchers to understand the memory retrieval process behind a creative process in design.

1.1. Different types of memory

Memories can be divided into three categories: sensory memory, short-term memory (STM), and long-term memory (LTM). Sensory memory is the information acquired through hearing, vision, touch, and other senses (Di Benedetto, 2007). For example, when a child is focused on watching a football game and a parent is speaking and asks the child to repeat what was said, the child can repeat the last sentence even if the child was not focused on what was said. This example of provides insight into how hearing-sensory memory works.

STM has a longer processing time (a few seconds or a few minutes). Unlike sense memory, which works unconsciously, STM allows people to repeatedly and consciously recall facts and events (Norris, 2017). Working memory is a special kind of STM. Working memory involves cognitive operations which can monitor, maintain, and control information related to tasks. Working memory replaces multi store models of memory where STM is weak in explanation. Working memory models seek to explain what will happen during short term or current processing. For example, higher cognitive load means lower attention, reduction of recall, and consolidation into LTM. Since working memory has more functions than STM, some researchers have argued that STM is a kind of working memory or that the concept of

STM should be replaced by that of working memory. However, based on existing research, the differences between working memory and STM are still not clear (Aben et al., 2012).

LTM is the memory that has been stored in the brain for a long time (Norris, 2017). LTM can be divided into two categories: declarative memory and non-declarative memory. Declarative memory is the memory that people can access consciously. It can be further divided into semantic memory and episodic memory. Semantic memory is the memory of facts that will not change and are not limited by time and space. An example of this is the fact that "the [current] capital of Australia is Canberra" (Beaty et al., 2020). Episodic memory consists of memories of events that the individual has experienced in a specific time and location, for example, "I ate some fruit yesterday morning" (Beaty et al., 2020).

Non-declarative memory works unconsciously. It can be subdivided into four categories: procedural memory, priming, associative learning, and non-associative learning. Procedural memory consists of the fixed skills formed in daily life, such as riding a bicycle. Priming is the ability that people have to react to stimulation based on what they have experienced shortly before. Associative learning is a type of memory formed by conditioned reflexes. Non-associative learning is a type of memory formed by habits (Baragli et al., 2015).

1.2. Memory and neuroscience technologies

Using functional magnetic resonance imaging (fMRI), researchers found that memory may be associated with the amygdale, an area of the brain that is related to emotional experiences and memory-forming (Dinar et al., 2015). With the help of EEG, researchers found that theta and gamma waves were associated with memory (Schack et al., 2002). When people are encoding and searching their memory, theta power increases (Klimesch et al., 1997). Some research has suggested that alpha waves are also related to memory because alpha waves are associated with understanding and analysing memories (McKay et al., 2003). It is important to note that memory processes can be divided into two types. One process is encoding memories, the other is extracting useful memories. In this research, the process referred to is the extracting memory process rather than the encoding process.

1.3. Applying neuroscience technologies to identify the relationship between memory and creativity

It is notable that there is significant literature in design applications using EEG, fNIRS, and fMRI, such as Nguyen et al. (2010) and Li et al., (2021). However, these studies mainly focused on association processes of creativity or the whole creative design processes instead of episodic and semantic memory retrieval. In other words, although there is significant literature in design using EEG, fNIRS, and fMRI, these papers have not focused on the episodic and semantic memory retrieval process in creative processes.

1.3.1. Short-term memory

STM is associated with Alpha, Delta, and Theta waves. STM is positively associated with Delta and Theta waves and negatively associated with Alpha waves. This is supported by Trammell et al. (2017) who asked 36 participants to recall 12 random words which had appeared before the task. In creative processes, STM can store relevant information temporarily (Gubbels et al., 2017). Mao et al. (2020) asked 24 students to "design a device that would cook burger patties consistently and automatically", use a pen to draw their idea on the computer, and name each part. In this study, the researchers found that STM stores information via chunking. Gubbels et al. (2017) tested the relationship between STM, analytical ability, and creativity. They asked children to look at 20 graphics and then write down a description of the graphics based on what they could remember. In addition, they asked the children to write down 10 words they heard and then rewrite them based on what they could remember. The results showed that (visual and language) STM affects analytical ability and the level of creativity.

1.3.2. Long-term memory

Creativity has a strong relationship with semantic and episodic memory (Beaty et al., 2020; Benedek et al., 2020). Semantic memory provides facts and concepts. These facts and concepts can be used as the source of new ideas (Goldschmidt, 1995; Kenett & Faust, 2019). Episodic memory includes both

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stimulating previous memories and reconstructing the details of previous events. The process of retrieving and combining previous memories can stimulate the imagination (Beaty et al., 2020) and, thus, supports creative generation of ideas (Madore et al., 2016). Benedek et al. (2020) asked participants to carry out two category fluency tasks (professions, types of sport), and two free association tasks (pure, funny). The results showed that the correlation between semantic and episodic memory and creativity is 0.39 ($p < 0.001$). The correlation is not strong, but it suggested the potential that semantic and episodic memory and creativity are related.
Some research has focused on the neural structure of semantic and episodic memory. In a creative process, the default mode network (DMN), which is associated with semantic and episodic memory, is activated (Benedek & Fink, 2019). However, since semantic and episodic memory are represented in the same area, it is hard to be sure whether it is semantic or episodic memory that is working when the DMN is activated (Beaty et al., 2020). Beaty et al. (2020) tried to detect the differences between semantic and episodic memory. They asked 28 young participants to undertake a DT test. Half of the tests consisted of episodic induction (EI) and the other half consisted of semantic induction (SI). fMRI was used to collect data. The results indicated that semantic and episodic memory can be neurally distinguished. Semantic memory is associated with left angular gyrus, left inferior parietal lobule (IPL), and posterior cingulate cortex, while episodic memory is related to the left parahippocampal gyrus and right IPL. However, these results have not been universally agreed on. For example, Green (2016) pointed out that the frontopolar cortex is related to semantic systems.

1.3.3. Non-declarative memory

Some research has shown that non-declarative memory can stimulate creativity (Huang et al., 2015). The caudate is considered the core region related to non-declarative memory. Huang et al. (2015) asked 18 students to identify whether the chunk division of certain Chinese words was correct. fMRI was used to record this process. The results showed that when thinking about novel things, the caudate part of the brain is activated. Since dealing with chunks has been proven to be associated with non-declarative memory (Wu et al., 2009) and since this is a kind of non-declarative memory form, the study supports the theory that non-declarative memory has a relationship with creativity.

1.4. Study aims

Existing studies have detected different neurophysiological characteristics of memory in creativity. However, these studies are limited. They mainly identified which parts of the brain or which kinds of wave bands were associated with creativity. Other EEG activities such as ERP are not fully explored. ERPs results can report small voltages generated in the brain structures in response to specific events. ERPs results based on EEG data is therefore worth exploring to further understand the EEG activities during memory retrieval in creative processes. To address these gaps, this study aims to identify the different EEG activities during memory retrieval in creative processes.

1.5. Memory types considered

This study focuses on LTM, especially episodic memory and semantic memory. Memory is a general concept that includes sensory memory, STM, and LTM. LTM can be further divided into declarative memory and non-declarative memory. Non-declarative memory is hard to test through EEG because it relates to unconscious processes, which cannot be controlled by participants. STM and sensory memory can be tested by EEG, but it is difficult for participants to report their STM and sensory memory. Therefore, this study focuses on declarative memory (episodic and semantic memory), which can be reported by people and identified by EEG.

2. Methods

2.1. Participants

Thirty Chinese participants (15 female, 15 male; aged 20 - 25) were recruited for this study (Stevens Jr & Zabelina, 2020). This sampling number was decided based on existing research (Cash et al., 2022) of

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Stevens Jr and Zabelina (2020), where thirty participants were recruited and EEG were used to understand participants' creative processes. All participants were professionals in industrial design or product design. All participants self-report that they are right-handed and have no barriers that would prevent them from using a computer, looking at a computer screen, or reading. They did not take any caffeine, unprescribed medication or alcohol in the three days before taking part in this study.

This study was approved by the local ethics committee of the institute of first author. An information sheet and the consent form were delivered before the study. Participants could ask any questions for clarification. If they did not have any questions, they were then asked to sign the consent form.

2.2. Methodology

Semantic and episodic memory retrieval ability in creativity were tested by adjusting Beaty et al.'s (2020) research procedure. The reason why we selected to adjust Beaty et al.'s (2020) research procedure on testing semantic and episodic memory retrieval ability in creativity was that Beaty et al.'s (2022) research was developed based on analogous to classic assessments of autobiographical memory retrieval and has been verified by various researchers such as Purcell and Gero (1998), Addis et al. (2007), Binder and Desai (2011), and Madore et al. (2019). In Beaty et al.'s (2020) research, semantic memory retrieval ability in creativity was tested by semantic induction tasks, where participants were asked to construct a creative sentence based on the given word. Episodic memory retrieval ability in creativity was tested by episodic induction tasks, where participants were asked to creatively retrieve related stored information based on the given words. However, participants may not be familiar with the prompt "creative". Therefore, based on the suggestion from Purcell and Gero (1998), we adjusted Beaty et al.'s (2020) induction task expression. In our study, in the semantic induction task, participants were asked to construct a sentence that few people would think of based on the word they were given in 20 seconds (Purcell & Gero, 1998). In the episodic induction task, participants were asked to retrieve related stored information that few people would think of based on the given words in 20 seconds (Purcell & Gero, 1998). It is notable that this adjustment did not change the task instead, it only changed the way the task was expressed to make it more easily to be understand by participants. Therefore, adjusting Beaty et al.'s (2020) research procedure helps to ensure validity and rigour in reference to best practices in this area.

Both task sections consisted of 30 trials. Each trial was presented once in the task section. For each task section, 15 trials were displayed based on words while the other 15 trials were displayed based on images, to avoid the bias generated from different task display forms. The words and word-related images used in the semantic memory and episodic memory task sections were different, but they were all taken from Beaty et al. (2020).

2.3. EEG recording and equipment

A Neurofax EEG-9200 system was used to collect the EEG signals. The device has 16 scalps (Fp1, Fp2, F3, F4, F7, F8, C3, C4, P3, P4, T3, T4, T5, T6, O1, O2) and 2 mastoid Ag/AgCl electrodes mounted according to the 10/20 system. The system included the EEG measurement system, amplifier, and software for viewing the EEG results. Impedances of all EEG channels were below 5 kΩ. The data were sampled at 1000 Hz. The semantic and episodic induction trials were presented on a computer screen (35.89 x 24.71 cm with a resolution of 2560 x 1600) with the help of E-Prime 3.0. The Neurofax EEG-9200 system was used to collect and store EEG data.

2.4. Procedure

Participants put on the EEG device with the help of the researchers. Each episodic induction task trial (30 trials in total) started with a fixation stage. In the fixation stage, a black fixation cross was presented on a light grey background for 2 to 5 s. A word was then presented on the next page and participants were asked to identify this word in 5 s but not verbalize it. If they identified the word before timeout, they could hit the "Space" key on the computer keyboard to go to the thinking interface. If the 5 s period ran out, the interface would jump to the thinking interface automatically. In the thinking interface, participants were asked to "retrieve stored information related with this word in 20 s but not verbalise it. This information should only be expected to be thought of by few people". If they finished the retrieval before timeout, they could hit the "Space" key to go to the next trial. An example of the trial is displayed in Figure 1.

Each semantic in duction trial (30 trials in total) started with a fixation stage. In the fixation stage, a black fixation cross was presented on a light grey background for 2 to 5 s. A word was then presented on the next page and participants were asked to identify this word in 5 s but not verbalize it. If they identified the word before timeout, they could hit the "Space" key on the computer keyboard to go to the thinking interface. If the 5 s period ran out, the interface would jump to the thinking interface automatically. In the thinking interface, participants were asked to "construct a sentence based on the given word in 20 s but not verbalize it. This sentence should only be expected to be thought of by few people". If they finished the retrieval before timeout, they could hit the "Space" key on the computer keyboard to go to the next trial. An example of the trial is displayed in Figure 1. The order of the semantic memory and episodic memory task sections was random. Participants could have a 5-minute break between the two sections. The two sections took about 20 minutes to complete in total.

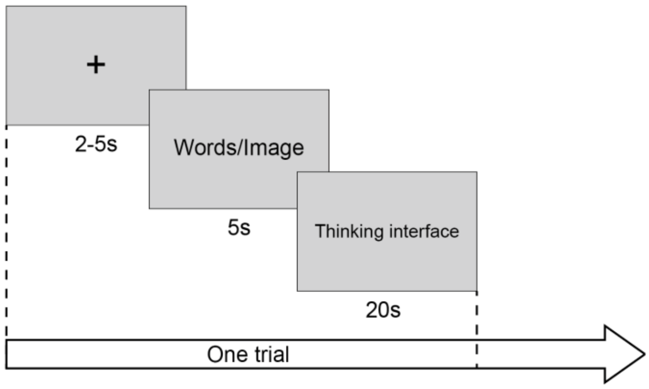

Figure 1. Example of each trial

3. The EEG data process

After the data collection, EEG signals were processed by EEGLAB. A 50 Hz notch filter was applied to remove electrical mains contamination. The signals were passed through a band-pass filter with a pass-band of 0.1–100 Hz (Schwab et al., 2014; Zarjam et al., 2011). Reference electrodes were placed on the left and right mastoid processes. For each task section, blink artifacts were removed with the help of independent component analysis (ICA). After this, ICA was repeated. The results of the new ICA identified 16 components (EEG activities) that were involved in the specific event.

4. Results

4.1. Independent component analysis and spectral analysis

The spectral analysis results reported the relative variances of components that were extracted from the ICA. Component percent relative variance represented the contribution of a specific component. The highest component percent variance which was associated with specific brain areas was used to identify which brain areas were activated in the episodic memory or semantic induction tasks. The top eight percent relative variances and their independent component from the semantic induction tasks are shown in Figure 2. The top eight percent relative variances and their independent component from the episodic induction tasks are shown in Figure 3. The results showed that semantic memory retrieval is mainly associated with the left frontal lobe (Fp1 channel) based on Component 7; while episodic memory retrieval is mainly associated with the frontal lobe (Fp1 and Fp2 channels) based on Component 8.

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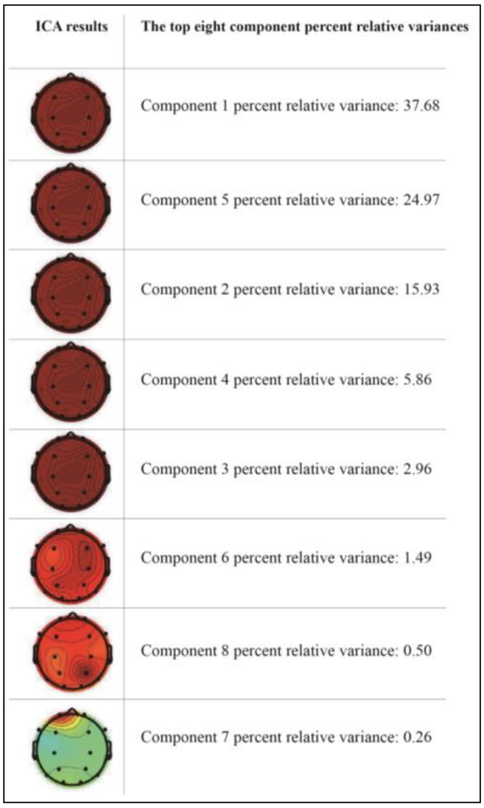

Figure 2. Results of semantic induction task results: the top eight component percent relative variances and their ICA results

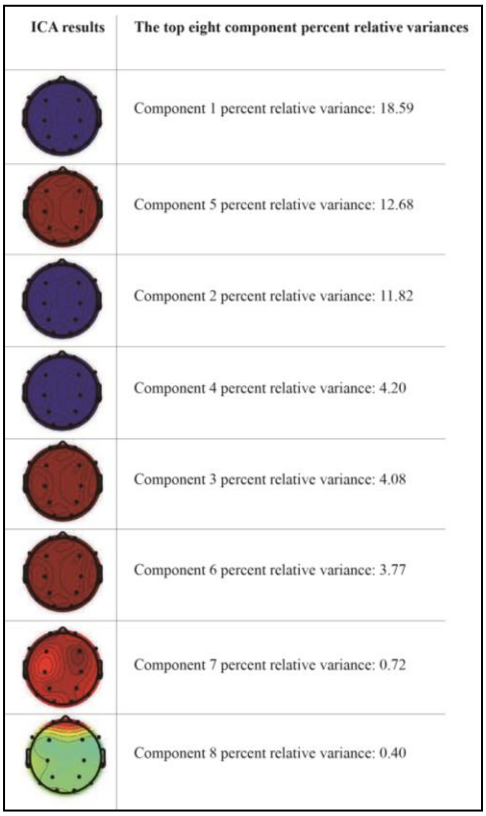

Figure 3. Episodic induction task results: the top eight component percent relative variances and their ICA results

4.2. Event related potential results

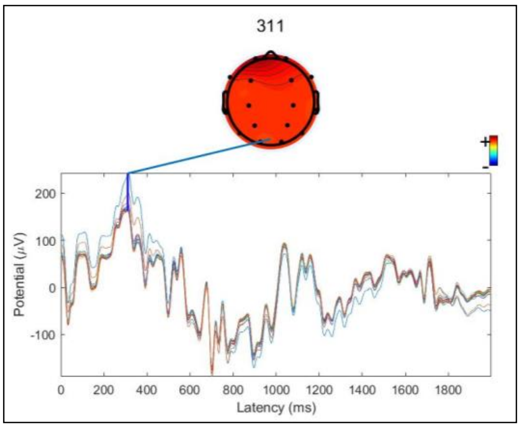

Figure 4. The highest ERPs results of the semantic induction tasks

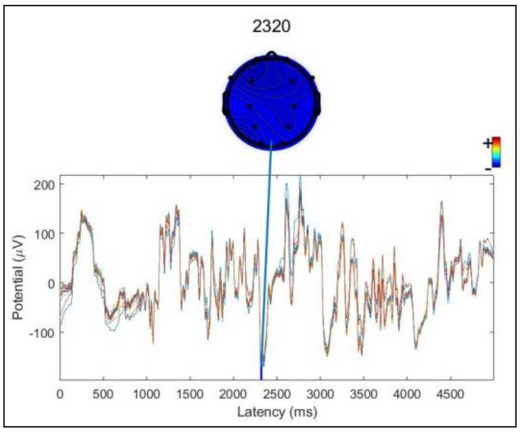

Figure 5. The highest ERPs results of the episodic induction tasks

After identifying the activated brain areas, the study further analyzed the ERP results of the episodic and semantic induction tasks. The ERP results were analyzed based on the related activated-brain-area EEG channels. The ERP results of the semantic memory and episodic induction tasks are shown in Figures 4 and 5 respectively. The results showed that the highest ERPs of semantic induction tasks was at 311 ms while the highest ERPs of episodic induction tasks was at 2320 ms.

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5. Discussion

This section discusses the results from this study on active brain areas and ERP and compares the findings of this study with existing research, identifies the limitations of this study, and outlines the prospects for future studies.

5.1. Active brain areas results

The results of this study show that the episodic memory retrieval in creative processes is associated with the frontal lobe. This finding differs from existing research which suggested that episodic memory retrieval is associated with the medial temporal lobe (Beaty et al., 2020). The selection of neuroscience tools may be the reason for this difference. Beaty et al.'s (2020) results were reported using fMRI while this study uses EEG to record data. In addition, in this study, the highest component percent variance (Component 8) was used as the cue to identify which brain area was activated in the episodic memory retrieval. The other components, which have relatively small component percent variances, were ignored. These ignored components may indicate that the episodic memory retrieval is associated with the temporal lobe area. The reason why these components were not included is that they are less likely to represent the brain areas of episodic memory retrieval in a creative process. However, less possibility is not the same as impossible.

The active brain areas of semantic memory retrieval in creative processes found from this study echoes existing studies (Green, 2016). Both of the studies supported that the semantic memory retrieval is associated with the frontal lobe area. However, the results of this study provided detail for this area to the left frontal lobe.

Our study has found that both semantic and episodic memory retrieval in creative processes were associated with the frontal lobe. This provides additional insight for research in creative design areas and allow further understanding of memory retrieval performance in a creative processes in design. For example, in future design cognition studies, it is worth paying more attention to the frontal lobe to further understand the memory retrieval processes in a creative design, especially in the creative idea generation process. In addition, the results of this study can raise the awareness on the importance of LTM for creative processes. Considering that the frontal lobe is related to divergent thinking, future studies could use EEG to detect how semantic and episodic memory retrieval influences creative design processes through affecting divergent thinking processes.

5.2. Event related potential results

ERPs can report the evoking time of events. From the ERPs results of this study, it can be found that the evoking time of semantic memory retrieval in creative process was 311 ms. Existing research has indicated various ERPs results for natural semantic memory retrieval such as 200 ms (Irak, et al., 2020), 300 ms (Paynter et al., 2009), and 400 ms (Undorf et al., 2020). This study specified that the ERPs of semantic memory retrieval in creative processes was around 300 ms (Mecklinger & Kamp, 2023). In addition, from the ERPs results of this study, it can be found that the evoking time of episodic memory retrieval in creative processes was 2320 ms. This evoking time was slower than existing research which mentioned that the ERPs of natural episodic memory retrieval is between 1000 to 1600 ms. This indicated that in a creative design process, designers may need more time to recall some events to get more inspiration.

In addition, the results of this study indicated that the episodic memory retrieval in creative processes requires more evoking time than semantic memory retrieval. Based on two different relations between episodic and the semantic retrieval in creative processes (distinct with each other or related with each other), some further findings can be summarized.

If the episodic and the semantic retrieval in creative processes are distinct, this longer evoking time for episodic memory retrieval may explain why in creative processes people are less likely to recall some events. The longer evoking time means that other cognitive behavior, such as semantic memory retrieval, may have more possibility to interrupt the start of episodic memory retrieval. Thus, the mind will turn from episodic memory retrieval to semantic memory retrieval. This finding can be used to trigger attention of designers that when they are involved in creative processes, they may need to consciously control the occurrence of episodic memory retrieval.

If episodic and semantic memory retrieval are related, the ERPs and evoking time results may indicate that semantic memory retrieval is fundamental to the episodic memory retrieval. When participants apply LTM in creative processes, semantic memory retrieval will occur first, followed by episodic memory retrieval based on the results of the semantic memory retrieval. This finding is supported by the ERPs results of the episodic induction tasks (Figure 4). Figure 4 showed that there is a high peak between 0-500 ms. This peak means that in the episodic induction task, some mind activities were evoked between 0-500 ms. This evoking was not as strong as that which occurred at 2320 ms and, thus, was not the evoking time of the episodic memory retrieval. Therefore, combining this evoking time with the evoking time of the semantic memory process, which was at 311 ms, it was assumed in this study that this evoking time between 0-500 ms in the episodic memory retrieval in creative processes was the evoking time of the semantic memory retrieval.

However, it is notable that based on the study, we cannot justify which is the real relations between episodic and the semantic retrieval in creative processes (distinct with each other or related with each other). This indicates a future worthwhile research direction of exploring the relationship between both semantic and episodic memory retrieval in a creative processes.

5.3. Limitations and future research

Some limitations exist in this study. Firstly, only 30 participants were recruited. This is a limited number and may not represent all cultures and ages. This, thus, may reduce the reliability of this study. In the future, more participants with a wider range of ages and cultures could be recruited. In addition, the study attempted to avoid spill-over effects (such as movement and noise). However, external interventions could not be completely ruled out. For example, each trial may have been affected by the previous one. One method that the study used was to limit the spill-over effects by presenting the trials in a random order as well as presenting two task sections in a random order. In addition, participants were asked not to move when thinking about the answers to semantic and episodic induction tasks. However, such an unnatural constraint on behaviour may affect the results.

Moreover, in this study, the creativity of episodic and semantic memory retrieval was represented by retrieving information or requiring participants to construct a sentence that only few people could be expected to think of. The creativity of these sentences and pieces of information was not quantified as it is not the core part of this research. However, in the future, the results of the episodic and semantic induction tasks can be collected to further identify the creativity levels of the results of episodic and semantic memory retrieval. Finally, the EEG results were collected from a 16-channel EEG device. Although the collected results have a saturation tendency as the channel numbers increase, it is not possible to say for certain whether the saturation point is 16 channels. Therefore, more EEG channels may need to be included in a future study.

6. Conclusions

The study aimed to identify the EEG activities (activated areas and ERPs) of episodic and semantic memory retrieval in creative processes. 30 participants were recruited to finish creative episodic and semantic induction tasks. During the process, EEG was worn to collect the brain signals. By comparing the differences in EEG activity between episodic and semantic memory retrieval, the results suggests that (i) episodic and semantic memory retrieval in creative processes are associated with the frontal lobe area. (ii) Episodic memory retrieval has a slower ERP result than semantic memory retrieval in a creative process. (iii) This study proposed an assumption that if semantic and episodic memory processes are related, in an episodic memory process, the semantic memory process will be evoked first, followed by the episodic memory process. The results of this study (i) Can help researchers and educators to better understand how people use LTM in their creative processes; (ii) Can be used as a pre-step to trigger researchers' thinking on how to use EEG to understand the creative process; (iii) Can raise the awareness of the importance of LTM for creative process.

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