Human memory retention and recall processes

A review of EEG and fMRI studies

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ABSTRACT

يعد مفهوم آلية ذاكرة الإنسان من المفاهيم المهمة في علم النفس المعرفي والعلوم العصبية. يشترك العقل البشري في أنشطة التعلم والحفظ. وبشكل عام تصنف ذاكرة الإنسان إلى مجموعتان ذاكرة قصيرة المدى وذاكرة طويلة المدى. باستخدام نماذج مختلفة للذاكرة وطرق الخرائط الذهنية تعرف أخصائيو العلوم العصبية والنفسية إلى 3 عمليات للذاكرة وهي عملية استقبال المعلومات، وحفظ المعلومات، ثم استرجاع المعلومات. وقد تمت دراسة هذه العمليات باستخدام الأشعة التصويرية والرنين المغناطيسي في أبحاث العلوم العصبية والمعرفية. في هذا السياق، نراجع الأبحاث التي تطرقت إلى آلية عمل الذاكرة باستخدام الأشعة التصويرية والرنين المغناطيسي، وصعوبات متعلقة بأبحاث العقل باستخدام طريقة الأشعة التصويرية والمقطعية.

Human memory is an important concept in cognitive psychology and neuroscience. Our brain is actively engaged in functions of learning and memorization. Generally, human memory has been classified into 2 groups: short-term/working memory, and long-term memory. Using different memory paradigms and brain mapping techniques, psychologists and neuroscientists have identified 3 memory processes: encoding, retention, and recall. These processes have been studied using EEG and functional MRI (fMRI) in cognitive and neuroscience research. This study reviews previous research reported for human memory processes, particularly brain behavior in memory retention and recall processes with the use of EEG and fMRI. We discuss issues and challenges related to memory research with EEG and fMRI techniques.

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In cognitive psychology, learning and memory are 2 closely related concepts, but they are not unitary processes. An essential part of our daily life is to attain new skills. We continue to learn new and different skills that enable us to perform in every phase of our life. We learn to walk, cook, drive a car, operate a computer, throw a ball, and play a game. We learn to fear hazardous circumstances and appreciate a particular type of music. We learn to speak and comprehend specific linguistics. We learn about personal autobiography, our own family tree, and world history. All of these skills are acquired through the learning process and retained in the memory for later use by other brain processes.[1] The purpose of this paper is to give a brief review of EEG and functional MRI (fMRI) studies on human memory processes involved in memory retention and retrieval/recall tasks, along with the diverse types of stimuli used in memory and cognitive tasks. Further, the aim is to highlight issues and challenges with EEG and fMRI techniques in memory research.

How many types of memories are there? Many theories and models have reported that the main types of memory are distinguishable according to capacity, processing speed, and storage span.[1,2] Theoretically, memory is classified mostly into 2 general categories: short-term and long-term. The terms "short-term" and "long-term" memory are used imprecisely to represent

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memory practices. Mark[3] defined the 2 main types of memory as follows: short-term memory (STM) is the competency to store evidence, data, and information momentarily for seconds before it is amalgamated into long-term memory (LTM); while LTM is the competency to learn new material (evidence, data, information) and recall this material after some time has passed.

Many studies have investigated the construct of working memory (WM), which refers to a capacity that temporarily stores a limited quantity of material in the brain for manipulation in order to help our learning and reasoning abilities.[3-6] Cowan[7] differentiated between LTM, STM, and WM, and he defined WM as one that includes a storage component analogous to STM, and further processing mechanisms that support the use of STM. Further, Engle[8] separated WM from STM and specified that WM is concerned with the attention related aspects of STM. Regardless of differences between WM and STM, in practice, the 2 can be used interchangeably,[9] which may indicate that there is slight discrepancy or close resemblance from a functional point of view between WM and STM.

The second main type of memory is the LTM storage, which is further divided into 2 sub categories; namely, semantic LTM and episodic LTM.[10,11] The concepts of semantic and episodic memory were introduced by Tulving.[12] According to Tulving, episodic memory refers to memory for personal events and temporal-spatial relations among these events, whereas semantic memory refers to structured knowledge that one has about real world entities (for example, symbols, words, and concepts), their meaning and relations with each other, and ideas about their use. In other words, episodic memory is concerned with and holds the "what," "when," "where" of daily life events, while semantic memory is related with facts that are strongly encoded in the mind and do not need any effort for retrieval.[11]

Besides these memory types, psychologists and neuroscientists have also investigated the memory processes - encoding, retention, and recall - associated with brain responses using memory tests and brain mapping techniques. For example, in neuroimaging, the fMRI is used, however, for brain electrical activities, the EEG is widely used. In the process of encoding, information from STM is transferred to LTM via involvement of the hippocampus. The hippocampus is the brain region responsible for encoding and memory formation. Battaglia et al[13] and Kryukov[14] recently reviewed the role of the hippocampus in the process of encoding and its various issues. Memory retention is the skill of the human mind to hold information in the brain for various durations, depending upon the type of memory and stimulus,[1,2,15] repetitions in recall,[16] levels of attention,[17] and emotion.[18] In the process of recall we recollect, stored material (for example, stimulus and event) in the brain via response(s) to some external stimulus.[1,2,15]

The subsequent sections describe reported brain regions related with memory functions, memory paradigms, EEG, and fMRI memory studies, issues, challenges, and conclusions.

Human memory. Chang et al[9] reported the Atkinson & Shiffrin Memory Model and related the workings of human memory with an information processing system, as shown in **Figure 1**.

According to the Oxford dictionary memory is defined as: "the mental capacity of holding evidences, actions, imitations, and so forth or recollecting earlier practices." Nevertheless, from the contemporary biological and psychological research perspective, the definition of memory, and regions associated with it are not so easily defined. Functionally, memory is defined as the capability to encode, hold, and subsequently remember material in the brain. From a psychological and neurological viewpoint, memory is the collection of encoded neural connections in the brain. It is the rebuilding of previous happenings and practices by a synchronous firing of neurons that were fired at the time of learning. **Table 1** presents the different brain parts with their related memory and cognitive responsibilities.

The human memory system is a complex system and is difficult to separate its components into different parts. However, in terms of time, capacity, and operations, it is typically divided into 3 types:[9]

(i) Sensory memory: The capability of holding sensory information from stimuli received through the 5 senses (visual, auditory, odor, taste, and tactile). Its time duration is very short and occurs in seconds. It

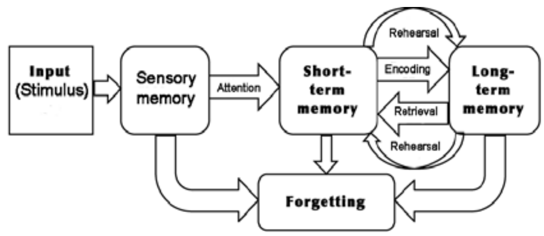

Figure 1 - Atkinson-Shiffrin Memory Model. Reprinted from Chang TWK, Chen NS, Yu PT. The effects of presentation method and information density on visual search ability and working memory load. ***Computers and Education*** 2012; 58: 721-731 with permission from Elsevier.[9]

Table 1 - Different brain regions with associated memory and cognitive functions.[19]

Brain parts	Memory processes
Frontal lobe	Working and STM
Temporal lobe	Hearing sense
Parietal lobe	Spatial memory
Occipital lobe (visual cortex)	Visual memory
Thalamus	Attention
Mamillary body	Episodic memory
Caudate nucleus	Memories of instinctive skills
Caudate nucleus (temporal, right)	Instinctive actions, e.g., grooming is stored here
Putamen	Procedural skills
Putamen (temporal, right)	Learning skills, e.g., the ability to ride a motorbike
Amygdala	Emotional memories
Hippocampus	Activated to transfer experiences into memories, e.g., STM to LTM
Cerebellum	Conditional memories, e.g., events linked by time
Central executive (frontal, right)	Holds entire plan, including visual elements

STM - short-term memory, LTM - long-term memory

works as a buffer in getting the stimuli via the senses (for example, eyes and ears). This information is then handed over from sensory to STM through selective attention.

(ii) Short-term memory: A temporary storage of small amounts of material for a short period, typically up to 15 seconds for approximately 7 items - information generated in STM due to paying attention to sensory memory.

(iii) Long-term memory: The collection of material over long durations of time; includes unlimited amounts of information.

Various studies have been reported on these memory types based on different conditions and different types of stimuli; for example, words, 2D images, digits, 3D objects, and sounds. Babiloni et al[20] investigated human cortical reactions by using a 2D simple visuo-spatial task of one bit to be memorized during STM. In the task, 2 vertical bars were used as a stimulus and subjects reacted after a 3.5 to 5.5 second delay time. No statistical difference between the 2 conditions was reported, but the EEG results revealed that during the delay period the power of theta (4-6 Hz) declined in the bilateral parietal regions and left frontal region. In addition, in the bilateral frontal and left parietal regions, low alpha power (6-8 Hz) was reduced, but a decrease was observed in high alpha power (10-12 Hz) in the left frontal-parietal areas. The author concluded that a very easy STM task results in alterations in the theta and alpha frequencies at the frontal-parietal region. In another EEG study, Babiloni et al[21] examined theta, alpha, and gamma changes in a visuo-spatial long-term episodic memory test during encoding and recall stages. The delay for the retrieval task was one hour. Their results suggested that eminent gamma reactions over the left parietal cortex are associated with encoding conditions, while retrieval processes are associated with the right parietal cortex. Burgess and Gruzelier[22] used words and faces as stimuli and examined memory-related changes in the EEG. At the temporal sites (T5/T6) and in the first 250 ms, they found the existence of a short duration increase in the theta range.

Kirov et al[23] presented that similar transcranial slow oscillation stimulation (tSOS) used in awakening the brain also causes a rise in EEG slow oscillations (0.4-1.2Hz), as well as an obvious and extensive rise in EEG theta (4-8Hz) activity. In awakened conditions, the tSOS failed to improve memory consolidation once used after learning, but a better encoding of hippocampus dependent memories was found when used in the course of learning.

Chang et al[9] studied WM load and visual search capability by using a change detection of 2, 4x4 dot arrays in successive and simultaneous forms of presentation with 3 various information density conditions of 75%, 50%, and 25%. Their results showed significant variations between the WM load and visual search capability at different levels of information density for the 2 different forms of presentation.

Jongsma et al[24] investigated the relationship of event related potentials (ERP) with learning and memory processes by using multiple digits learning trials. They observed corresponding memory improvements in the middle of the stimuli sequence. The study used auditory digits as the stimulus and free recall task for measurement of memory performance such as recalling items in correct position in the sequence. They concluded there was a close correspondence between memory performance and amplitude of ERP component - P300.

Memory retention and recall processes. Memory retention and recalling are key memory processes. Retention is the capability to hold information, and retrieval is the recollection of held information in the mind in response to external stimuli. Cognitive research literature[1,15,16] has highlighted that these processes are related to one another and also to factors such as learning, testing, and capacity limit of memory, attention demand, and complexity of material. The conventional concept of learning and retrieval is that learning takes place during events of studying, while retrieval helps to assess the learned contents. Psychologists studied learning by trials of study (S) and a test (T). The critical assumption is that learning happens during study phases while retrieval (test) simply measures contents learned in past study phases (of STSTST…order). The same theory is followed in educational systems, learning occurs during lectures, reading, and study groups. Tests have been designed to judge what has been absorbed or learned by studying. These tests are considered assessments or evaluations of learned knowledge.

Recently, a study of reviewed evidence opposes this conventional perception: retrieval exercises during tests have often-caused better learning and long-term retention than studying.[25] In similar studies, Karpicke and Roediger[16,26] experimentally examined retention related to learning with repeated testing, and they suggested that the repeated recalling of held information led to better learning and long-term retention. In one experiment, participants were given a list of items to study under 2 different conditions. In one condition, the list was studied 15 times and tested 5 times, while in the other condition the list was studied 5 times and tested 15 times. A retrieval task after one week showed better learning and retention results in the repeated test condition cohort as compared with the repeated study cohort. In another study, Marois and Ivanoff[27] reviewed capacity and processing limitations of the brain on visual STM and emphasized 3 limitations: (a) the time required to identify a visual stimulus, (b) the number of visual stimuli that can be held in STM, and (c) the selection of suitable response for a stimulus. Diamantopoulou et al[28] used different categories of stimuli and studied memory capacity and memorization. They argued that estimates of memory capacity and memorization were more dependent on resemblances in stimuli. The behavioral results of the study suggested increased response times and error rates with memory load.

Karlsgodt et al[29] conducted a fMRI study that used a verbal WM test. In encoding, maintenance, and recall, a within-subject comparison of functional activation suggested that the hippocampus had a role in WM like the one it had in LTM; implying that the hippocampus might be involved in overall encoding and recalling rather than just in LTM tasks.

Bankó and Vidnyánszky[30] used a delayed facial emotion discrimination task in which 2 faces (sample and test) were used as a stimulus. The stimuli comprised a frontal view of faces with slowly varying emotional expression of happiness. Two faces were presented for 300 ms with 2 different retention intervals, either 1-s or 6-s inter-stimulus-intervals. They explored the STM processes for facial emotional features and concluded that the retention interval tempers neural processes in the STM encoding process.

Joiner & Smith[31] studied the effects of slow and fast learning processes on memory retention. They found that the slow learning process strongly contributed to LTM more so than a fast learning process.

Effects of content on memory. Different theories exist regarding the effects of contents,[32] modalities,[32] presentation modes, and stimulus types[33] on memory processes and brain responses. Khairudin et al[34] used stimuli of words and pictures to investigate the effects of emotional contents on explicit memory. Words and pictures were presented in positive, negative, and neutral categories in 2 separate experiments. Their results suggested evidence of better memory performance for pictures than for words, and the comparison of positive with negative stimuli indicated that positive stimuli in explicit memory were remembered better than the negative. Thus, they concluded that negative content suppressed explicit memory. In another study, Crottaz-Herbette et al[32] observed modality effects in verbal WM. They employed fMRI with analogous stimuli and investigated the resemblances and variances between visual verbal WM and auditory verbal WM. They examined similarities and differences during visual and auditory tasks in brain activation. The statistical comparison presented significant modality effects in the activation of the prefrontal and parietal cortex, as the left dorsolateral prefrontal cortex (PFC) showed greater activation in auditory verbal WM. However, in visual verbal WM, the left posterior parietal cortex was highly activated when compared with auditory verbal WM processing. No such variances were found in the right hemisphere. Grady et al[35] used words and pictures of objects as different types of stimuli and investigated the effects of stimulus types in the right PFC in recognition memory. They observed that the number of correctly recognized items was larger for object stimuli than for words, and that the response time was significantly faster for objects than for words. Lee et al[36] investigated the effects of verbal and visual stimuli on memory processes in episodic memory. Their study found that in left lateral PFC, verbal memory tasks were related with regional cerebral blood flow changes, while visual memory tasks were associated with changes in the right lateral PFC. Maass et al[37] examined the effects of 2 different computer game contents on memory performance, learning, and information processing in adolescents. They compared the effects of violent versus non-violent game contents under 2 conditions: playing, and watching. The results suggested that violent content had a negative short-term impact on learning and information processing. Eng et al[38] measured visual WM capacity for 6 types of stimuli: faces, cubes, polygons, squiggles, colors, and letters of diverse complexity. They concluded that estimated visual WM decreased for stimuli that were more complex. **Table 2** summarizes memory studies of investigated content effects on memory processes.

Memory paradigms. We found numerous memory paradigms in the literature for learning, memory types (WM, STM, LTM), memory processes (retention, recalling, encoding) for different stimulus (visual, auditory), and complexity level (easy, hard). Many of these paradigms are commonly applied in cognitive studies. **Table 3** presents a list of memory paradigms currently in practice in memory research.

Modalities and memory research. In this section, we concentrate on the 2 most commonly used modalities; namely, EEG and fMRI.

Electroencephalography. The EEG provides a large scale, robust measure of neocortical dynamic function.[57] The EEG analysis is a comprehensive analysis of the brain's electrical field at the scalp's surface due to its direct measurement of brain neuronal activity with high temporal resolution. It consists of several frequency bands associated with different brain states. **Table 4** summarizes common frequency bands related with brain states and activation regions.

Table 2 - Summary of memory studies investigating content effects on memory processes.

Study	Contents/modality	Memory processes	Findings	Subjects	Status	Age (mean)
Grady et al[39]	Pictures and words	Recognition memory	Picture stimuli were recognized more than words with a faster response time than words	12	Normal	Mean: 25.6
Duarte et al[40]	Objects (pictures) and words	Recognition memory	Source memory related activity differs according to the nature of stimulus materials	15	Normal	18-32
Lee et al[36]	Verbal and non-verbal stimulus	Encoding and retrieval in episodic memory	95.7% of verbal material was retrieved compared with 94% visual material	8	Normal	21-61
Maass et al[37]	Violent versus non-violent computer game	Memory and learning	Violent content has a negative short-term effect on information processing and learning	167	Normal	Mean: 17.6
Velisavljevic and Elder[41]	Coherent and scrambled images of natural scenes	Recognition performance in STM	Contents near the center of the frame were better memorized	10	Normal	20-34
Van der Ham et al[42]	Large and small cross dot	WM performance	Coordinate performance was accurate with the small cross and categorical processing was faster with the large cross	33	Patients	18-80
Testa et al[43]	Objects, words, and faces	Recognition memory	Memory ability was better for objects and faces but poor for words stimuli with LTLE patients. Memory performance was good for objects, words, but relatively poor for face stimuli in RTLE patients.	63	Patients	
Prince et al[44]	Faces and places	Encoding and retrieval	Right FFA was associated with memory in encoding and retrieval processes, while left FFA was linked with memory in encoding only in face sensitive areas Left PPA was related with positive memory in encoding and retrieval; while right PPA was related with positive memory in encoding only in the sensitive area	19	Normal	Mean: 27.7
Levens and Phelps[45]	Emotional versus neutral stimuli (words and pictures)	Interactions between emotion and interference in WM	Significantly longer RT for interference trials than non-interference trials. Interference found reduced conflict in trials with emotional stimuli	44	Normal	18 or above
Berti and Schroger[46]	Auditory and visual distractor stimuli	WM	Highly significant difference in RT between auditory and visual modality	10	Normal	19-29

STM - short-term memory, WM - working memory, LTLE- left temporal lobe epilepsy, RTLE- right temporal lobe epilepsy, FFA - fusiform face area, PPA - para-hippocampal place area, RT - reaction time

Table 3 - List of different memory paradigms applied in memory studies with pros and cons.

Paradigms	Purpose	Pros	Cons
Sternberg memory task[47]	STM	Encoding, retention, and retrieval processes are not overlapping	Low manipulation
Spatial delayed response task[48]	Short-term and long-term delayed response	Highly used for visual memory and location assessment	Creates boredom in participants when tasks require longer delays with many conditions and trials
Self-ordered pointing task[49]	WM	Useful to assess executive functions	Limited to WM content
Running span task[50]	WM	Increased attention demand	Recency effect
PASAT[51]	WM, information processing, and attention	Widely used for patients with multiple sclerosis	Creates anxiety and frustration in participants due to high rapid response demand in PASAT
N-back task[54]	WM	Manipulation and updating processes are involved	Encoding, retention, and recalling overlap
Karpicke & Roediger learning task[16]	Learning and retrieval in LTM auditory	Useful for testing effects on learning and memory	Specific to LTM retrieval only
Auditory digit span test[53]	Auditory STM and WM	Helps assess the ability of auditory information processing and its capacity	Specific to auditory memory only
Visual digit span[54]	Visual STM and WM	Able to evaluate the ability of visual information processing and its capacity	Limited to digits and visual memory only
Corsi block tapping task[55]	Visual memory	Useful to assess visuo-spatial memory in patients with brain injury	Limited to visual stimulus with location only
Oddball task[56]	To observe the ability of target detection	Assesses neural reactions to unpredictable and recognizable events, and studies ERP signal	Stimuli dependent, synchronization required

PASAT - Paced Auditory Serial Addition Test, ERP - event related potential, STM - short-term memory, LTM - long-term memory, WM - working memory

Table 4 - Electroencephalography (EEG) frequency bands with related brain parts.

Frequency Band	Range (Hz)	Brain region	State
Delta	0.5-4	Thalamus	Deep sleep in adults
Theta	4-7	Hippocampus	Dreaming sleep
Alpha	8-12	Posterior regions, central cites at rest	Relax, close eye, awake
Beta	13-30	Frontal region	Alertness and concentration
Gamma	Above 30	Somatosensory cortex	Sudden bursts

Changes in EEG activity during STM/WM and LTM memory task performance in encoding, retention, and retrieval processes were reported mostly in theta and alpha bands and rarely in other ranges. Harmony et al[58] investigated delta bands during mental tasks that required mental internal processing by performing 2 experiments: (i) a tough mental calculation task with a control stimulus and (ii) the Sternberg task for STM analysis adopting either a 3 or 5 digit memory load. Stimuli were shown randomly in both experiments. The study found increased delta power between 1.56 and 3.90 Hz in mental tasks that were dependent on task difficulty. Klimesch[59] reported that short-term episodic memory loads caused an increase in theta band power, which implies more synchronization. The study also suggested changes in theta power in the anterior limbic system. Grunwald et al[60] reported theta power changes in the handling of diverse complex haptic stimuli by a delayed recall design. During the retention interval, the study found a direct association between theta activity over electrode sites (Fp1, Fp2, F3, F7, F8, C3), corresponding to frontal-central regions with a mean assessment time for complex haptic stimuli. The observation indicated a functional association between the brain's electrical activity and WM processing in the theta bandwidth. Wilson et al,[61] studied the effect of task difficulty and the temporal effect related to keeping items in memory before memory recall. There was a significant increase in response during the retention period for the most difficult tasks at frontal

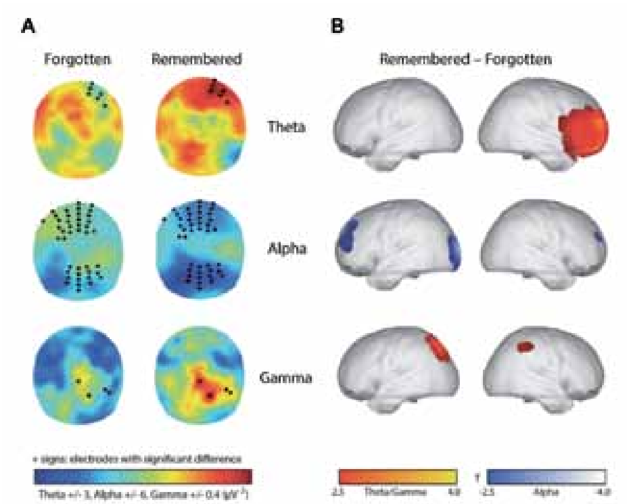

Figure 2 - The EEG theta, alpha, and gamma activity changes during memory encoding, maintenance, and retrieval processes are shown. **A**) Depicts averaged power of theta, alpha, and gamma under 2 conditions; namely, item remembered and forgotten. **B**) Depicts estimated source localization of subsequent memory effects (remember versus forgotten). In the left panel, electrodes are marked where the difference between SR and SF is significant. Reprinted from Friese U, Köster M, Hassler U, Martens U, Trujillo-Barreto N, Gruber T. Successful memory encoding is associated with increased cross-frequency coupling between frontal theta and posterior gamma oscillations in human scalp-recorded EEG. ***Neuroimage*** 2013; 66: 642-647 with permission from Elsevier.[63]

and occipital-parietal sites. Jensen et al[62] observed that during STM retention tasks the power of the alpha band [9-12 Hz] improved with increased memory load. The results indicated that the alpha peak steadily increased with an increase in the number of objects held in WM. This result differs from earlier reports that alpha power declined due to memory load in diverse WM. This contradiction may be due to the type of memory task used, because reports claiming that alpha power decreased with memory load used the n-back memory task, while reports claiming that alpha power increased with memory load used the Sternberg task.

Friese et al[63] investigated the functional relationship between EEG frontal theta, prefrontal and occipital alpha, and posterior gamma activity during successful memory formation as shown in **Figure 2**. They observed enhanced cross-frequency coupling between frontal theta phase and posterior gamma power during the encoding of visual stimuli in 2 conditions; namely, subsequent remember (SR) and subsequent forget (SF). High theta in frontal, high gamma in parietal, low alpha in prefrontal and occipital regions were associated with successful memory encoding, maintenance, and retrieval processes. This study demonstrated the interaction between frontal and posterior brain regions during new memory formation. **Table 5** presents a summary of EEG studies that investigated memory and cognitive tasks.

Event related potential. An ERP is a measurement of brain response as a direct consequence of an external stimulus. In other words, ERPs are time-locked voltage fluctuations in the EEG signal.[57] For example, when repeatedly presenting a visual stimulus, the event will evoke an EEG change. The change that appears in the EEG signal after the stimulus is the ERP. One of the most highly investigated ERP components in cognitive

Table 5 - Summary of EEG studies that detected changes in EEG frequency bands during memory tasks.

Study	Cognitive tasks	Memory paradigm	Changes in EEG frequencies	Changes found in brain regions
Kalimesch[59]	LTM (semantic) retrieval	-	Theta synchronization, upper alpha, de-synchronization	Hippocampo-cortical feedback loops, in thalamo-cortical feedback loops
Jenson and Tesche[64]	WM (retention process)	Sternberg task	Theta [7-8.5 Hz] increases	Frontal region
Brookes et al[65]	WM	Sternberg and N-back tasks	Theta power increased and modulated with task difficulty	Medial frontal cortex
Park et al[66]	Visual STM; memory load and encoding in visual STM	One-shot paradigm	Theta [5-10 Hz], increase power, beta power decreases	Frontal region, parietal-occipital region (O1, O2, Pz, and POz)
Khader et al[67]	WM maintenance	Delayed matching-to-sample task	Theta power increases, alpha power increase	Mid-frontal (Cz, Fz), parietal-occipital cortex
Jaiswal et al[68]	Encoding in WM	Spatial memory task	Theta activity increases, alpha higher activity	Right frontal region
Bastiaansen et al[69]	Memory retrieval	Delayed 2-choice reaction time task	Theta [4-7 Hz] power increase	Left occipital region
Kalimesch[59]	Memory performance		Alpha de-synchronization	Thalamo-cortical
Harmony et al[58]	Calculation	Arithmetic task	Alpha [12.48] decrease	Left parietal cortex

LTM - long-term memory, STM - short-term memory, WM - working memory studies is P300, which normally appears between 300-600ms after stimulus. The P denotes positive amplitude and 300 represents 300ms post-stimulus. Its amplitude is sensitive with stimulus probability. Polich[70] reviewed fundamental issues, theoretical overview, and neuropsychological background of P300 in detail. A number of neurocognitive studies have been reported on correlations between ERP and memory,[71,72] especially between the P300 component and the memory processes and learning.[24,73] Ergen et al[72] investigated the P300 response in STM retrieval by a using multiple probe Sternberg task with 2 memory loads comprising 3 and 5 letter memory sets. They found longer reaction times (RTs) due to increasing memory load and shorter RTs for the positive probe compared with negative probes. Furthermore, they also observed an increased latency of P300 with the increased memory load of the 5-letter set, and a shorter latency for the positive probe compared with negative probe. They concluded from the topographic analysis that the right lateralized positivity of 200-250 ms reveals that the memory scanning process and P3 peak with midline parietal topography reflected the decision making process.

Wisewede et al[74] investigated the serial position effect (typically called u-shape curve) with ERP in learning. Results demonstrated frontal region activation for items at the beginning of the list, while parietal brain area was associated with items at the end of list. High amplitudes of P300 were observed for recalled items on primacy position compared to recency at central electrodes (FPz, Cz, Pz). In contrast, Jongsma et al[24] studied recall performance with ERP in digit learning tasks. They focused on the middle items of a list for recall as compared with beginning and ending items, and observed positive changes in P300 amplitudes that occurred during learning for middle items in the list due to repetition.

Functional magnetic resonance imaging. The fMRI has become the most important and commonly used method for brain imaging research. It uses MRI and local oxygenation of blood to determine changes in brain activity.[75] During any activity in the brain, when neurons become active; they consume more oxygen. Thus, more blood is required to meet the amount of oxygen in that particular brain area. The fMRI measures brain signals based on blood oxygenation changes and is known as BOLD (blood oxygenation level dependent) signal. For more details about fMRI components and data analyses see Poldrack et al,[75] as well as Ullsperger and Debener.[76]

Numerous fMRI studies have been investigated for different cognitive operations; for example, attention, perception, imagery, language, working, semantic memory, semantic memory encoding, episodic memory retrieval, and procedural memory.[77] The fMRI studies have shown a robust relationship between mental processes and activation in areas of the PFC. The PFC has distinctive activation forms for diverse cognitive functions such as sustained attention, smell, insight, written word recognition, spoken, and spatial WM, semantic memory, and episodic memory.[78] Manenti et al[79] investigated long-term retrieval (episodic memory) in an experiment consisting of 2 phases, encoding and retrieval, using the fMRI. The study suggested that the left dorsolateral PFC might be involved in memory retrieval. Song and Jiang[80] used 3 different stimuli (color only, shape only, both color and shape) for visual WM tasks. Their fMRI findings explored the involvement of different brain regions (frontal, parietal, and occipito-temporal) in the tasks. They found that the posterior parietal cortex was sensitive to feature complexity (for example, shapes) and memory load manipulation, while the prefrontal was sensitive to load manipulation only.

Todd et al[81] used 2 different categories of stimulus (color and faces) in an fMRI study and investigated visual WM encoding. **Figure 3** presents the task trial design for fMRI study using 2 different types of stimulus. They found a significant difference between participants' encoding time, that is, more information was encoded into visual WM for facial stimuli (presented for 1500ms), while the response time was faster for

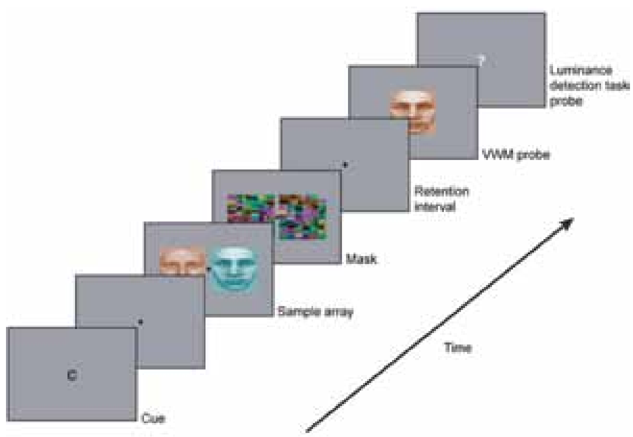

Figure 3 - A task designed for fMRI study to investigate visual working memory (VWM) encoding for 2 different types of stimuli: colors and faces. The color stimulus needs 50 ms while facia stimulus requires 500 ms to be fully encoded. Reprinted from Todd JJ, Han SW, Harrison S, Marois R. The neural correlates of visual working memory encoding: a time-resolved fMRI study. ***Neuropsychologia*** 2011; 49: 1527-1536 with permission of Elsevier.[81]

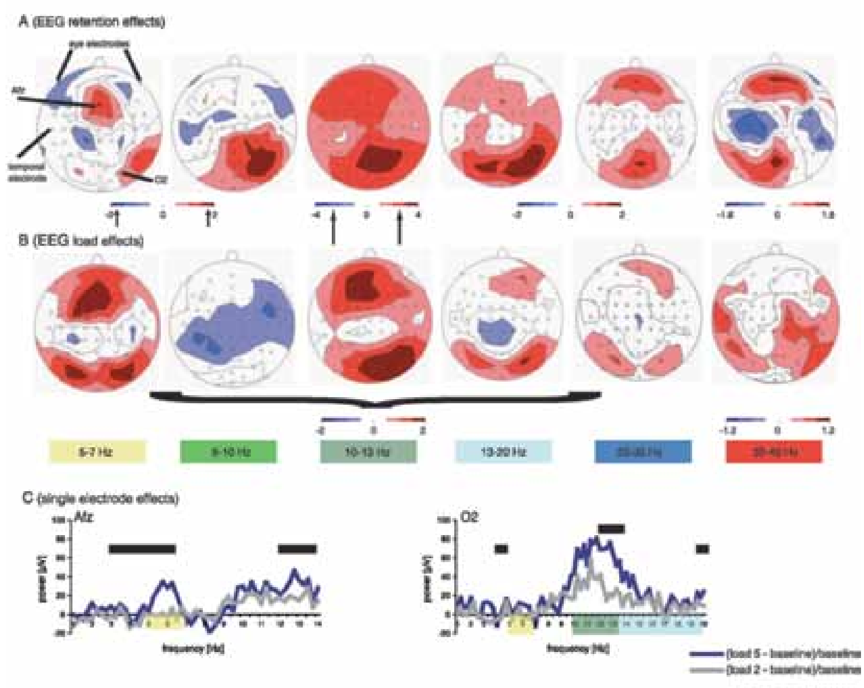

Figure 4 - Results of EEG during retention interval showing **A**) EEG retention effects, **B**) EEG load effects, **C**) EEG single electrode and single electrode effects. Reprinted with permission from Michels L, Bucher K, Lüchinger R, Klaver P, Martin E, Jeanmonod D, et al. Simultaneous EEG-fMRI during a working memory task: modulations in low and high frequency bands. ***PLoS One*** 2010; 5: e10298.[33]

color stimuli. An EEG-fMRI study[33] investigated EEG high and low frequency bands using the Sternberg WM task and reported a significant increase in theta (5-7 Hz) power at frontal sites, while alpha 1/2, beta 1 (13-20 Hz), some parts in the beta 2 (20-30 Hz) and gamma bands showed enhanced spectral power in the parieto-occipital region. **Figure** 4 depicts low and high frequency bands. All frequency bands except alpha 1 showed a positive increase with set size during the retention period (**Figure 4B**) during the load dependent analysis. During the retention period of the WM task, they examined the association between EEG bands and fMRI BOLD signals and demonstrated that both higher and lower frequencies correlated with BOLD signals. **Table 6** presents a summary of fMRI studies in memory processes.

Issues, challenges, and recommendations. In this section, we discuss key issues and challenges that arise in the design and study of memory research and some technical limitations of EEG and fMRI techniques. We will also review various ethical issues that are essential considerations when using EEG and fMRI methods and a few recommendations for future research. Many theoretical, practical, and ethical issues[88,89] are cited in the literature on human memory research. Brockmole,[90] and Davies and Wright[91] described current issues in memory research, especially in visual spatial memory, and applied memory research. In this review, we summarize common issues related to neurocognitive research design.

Memory categories. As discussed earlier, researchers differentiate memory types (STM, WM, and LTM) according to capacity, retention duration, and speed of processing. In the design of cognitive experiments, memory types are essential in the specification of other experimental parameters as mentioned below.

Memory modality. In learning and memorization processes, 2 modalities, visual and auditory, play a vital role. The brain processes information received from visual and auditory memory differently, and capacities vary between visual memory and auditory memory.

Targeted brain region. As the brain consists of many parts and lobes depending on respective function (**Table 1**), in the case of an injured brain, researchers have designed special tasks that target specific areas of the brain. Characteristics of the sample: Samples represent an individual's participation in the experiment and from whom the data are collected. The characteristics of a sample may be healthy/normal subjects or patients, old or young, adolescent, or children, and male or

Table 6 - Summary of fMRI studies investigating memory processes.

Study	Stimulus tasks	Memory type	Retention interval	Brain regions	Results	Subjects	Normal or patients	Average age
Donohue et al[82]	3 types of road signs: familiar, novel but explained, novel not explained	LTM	-	VLPFC, posterior middle temporal gyrus	Left posterior MTG was more activated for known signs than unknown signs. Right VLPFC was more active for novel explained signs than for novel unexplained or familiar signs	14	Normal	20-30 mean = 23.3
Zysset et al[83]	Sternberg task	LTM retrieval	-	Premotor, left prefrontal, left precuneal and parietal regions	No additional area involved with increase of list from short to long list	9	Normal	21-25
Henson et al[84]	Five tasks	Verbal STM	-	Posterior temporal regions and dorsolateral premotor cortex	Left posterior temporal areas for verbal item, and left supramarginal gyrus for short-term storage	6	Normal	22-30 mean = 27
Ranganath et al[85]	Face detection	WM and episodic LTM	WM: 7 second delay, LTM: 5-10 min	PFC	Common regions of dorsolateral, ventro-lateral, and anterior PFC were all activated during both WM and LTM tasks	8	Normal	19-40
Veltman et al[86]	Sternberg, n-back task	Verbal WM	-	Bilateral dorsolateral and anterior prefrontal, left ventro-lateral prefrontal, and bilateral parietal regions	Sternberg and n-back activated identical regions, but for different extents	22	Normal	Mean = 22.7 +-3.6
Campo et al[87]	Verbal and spatial task	LTM encoding	2500ms	Medial temporal lobe	Left MTL activated for verbal encoding, while right MTL activated for spatial task	8	Normal	24-37, mean = 29.22

LTM - long-term memory, VLPFC - ventro-lateral prefrontal cortex, MTL - medial temporal lobe, PFC - prefrontal cortex, WM - working memory, STM - short-term memory, MTG - middle temporal gyrus

female. These characteristics have roles that determine the experiment's duration and the complexity of the cognitive tasks.

Brain mapping technique. Two common methods of recording brain responses are EEG and fMRI as discussed. Both methods have limitations and advantages. To overcome these limitations, simultaneous EEG-fMRI results have been reported in recent studies.[92-94]

Memory paradigm. As discussed, several memory paradigms exist, even multiple paradigms for the same memory investigations are utilized to present stimuli in an experiment; for example, Sternberg and n-back for WM. As per hypothesized outcome, we must identify the memory paradigm that best reflects a subject's responses.

Length of experiment. Subjects may exhibit anxiety while taking part in EEG/fMRI experiments due to a prolonged experimental period. This in turn affects the individual's attention and interest in the experiment and ultimately affects the desired outcomes. Thus, according to an individual's health, research objectives, and specified modality, the experiment duration should be fixed.

Difficulty of cognitive task. In many cognitive studies, complex tasks have been used to investigate memory load and processing speed, but unnecessary complexity in shorter time intervals may lead to missed or unintentional responses by the individual. This is a very critical issue based upon several parameters such as memory type, subject health and age, and the nature of the memory.

Subjects' agreement. In neuro-cognitive research, the individual's consent is an important issue. The experiment should meet regional legal and ethical laws in order to protect the individual's wellbeing, mental privacy, and self-incrimination.

The EEG signals are multidimensional, non-stationary, and time domain biological signals. Due to the dynamic nature of EEG signals with high temporal resolution and the volume of data sets, automatic compilation of EEG data is a huge challenge, especially with the introduction of high density EEG nets with higher sampling frequencies of 1000 Hz and above.[95] Additionally, as the EEG signal consists of a substantial amount of noise and artifacts, and the precise determination of the source is poor, the extraction of information presents a massive challenge. However, many soft computing methods exist for EEG processing,[95] but there is no "decent" or "poor" method for EEG analysis. Hence, the selection of technique for EEG processing depends upon the data set and the analytical objective. An elementary issue with EEG is how to approximate the neuronal sources responsible for the recorded distribution of electrical activity at the scalp.[96] In other words, this issue is an inverse and ill-posed problematic result of the EEG technique that has no singular solution though many possible solutions exist for any given scalp recording.[97] Thus, EEG source estimation requires suppositions as to the nature of the sources. Many strategies are available for solving EEG source localization or the inverse problem; for example, low-resolution brain electromagnetic tomography (LORETA),[98] and standardized low-resolution brain electromagnetic tomography (sLORETA).[99] These strategies are now very common, due to comparisons of source estimation results with neuroimaging techniques, for example, with fMRI, have found substantial overlap. A comparison example of such a study was provided by Mulert et al.[94]

Recent developments in EEG recording equipment, and analytical approaches have made it a widespread and potential brain mapping instrument that directly records neuronal activity using acceptable spatial and high temporal resolutions. As a result, signal-source association has improved. A recent study described the limitations and strengths of EEG technology and declared some of the cited drawbacks of EEG; namely, misinterpretation and misunderstanding.[100] They concluded that despite these limitations, spatial analysis of the EEG acceptably determines sources for scalp signals. Furthermore, the strong features of EEG; for example, excellent high temporal resolution, plasticity, lower cost, ease of use, and high density EEG reading, render it the dominant technology for brain mapping.

The fMRI has good spatial resolution (in millimeters) but poor temporal resolution (few seconds). A good understanding of neural function correlates mental processes that require temporal data reliably provided by EEG measures.[77] One study reviewed the fMRI study design's features; for example, cognitive comparison strategies, stimulus presentation (for example, block, event related, self-driven experiment), and technical limitations (for example, signal to noise ratio, spatial, and temporal resolution).[101] There is a trade-off between spatial resolution, temporal resolution, and brain coverage in the fMRI method. Thus, it remains a challenge for researchers to make the best use of these parameters in fMRI experiments. **Table** 7 summarizes issues in EEG and fMRI methods.

Table 7 - Summary of issues and challenges in EEG and fMRI techniques.

Study	Issues	Modality	Challenges	Recommendation
Pascual-Marqui et al[98]	Inverse problem	EEG	Estimation of neuronal source	LORETA
Menon and Kim[102]	Spatial and temporal limits	fMRI	Spatial resolution in millimeters; temporal resolution in seconds	Single trial task fMRI studies facilitates increased spatial resolution
Poldrack[103]	Cognitive process issue	fMRI	Reduced subject anxiety in experiment	Anxiety can be reduced via experience with the scanner in a single imaging session
Matthews and Jezzard[104]	Study design issues	fMRI	Time efficiency and event related responses in fMRI	Block design is the most time efficient method to compare brain responses in various states/stages of the experiment
Amaro and Barker[101]	Study design issues (block design, event related), and technical limitations (spatial, and temporal resolution SNR)	fMRI	Brain coverage must be reduced when temporal resolution is fixed and spatial resolution is increased; when brain coverage is maintained and spatial resolution is increased, then temporal resolution must be reduced but may cause longer experiment time	Select right voxel size as per scanner specification and targeted brain area
Pike[105]	Indirect measurement of synaptic activity of BOLD signal	fMRI	The clarification of the dynamics of cerebral blood flow, blood volume, and metabolism of oxygen. The use of BOLD fMRI in stroke patients to examine the functional status of brain tissue in the stroke region	The quantitative fMRI method is available, but to adopt and adapt it to affect patient care, the method will have to be more robust, faster, and easier to use

BOLD - blood oxygen level dependent, SNR - signal to noise ratio, LORETA - low-resolution electromagnetic tomography

Ethical issues are an important component of brain research. Our thoughts and ideas are highly private and with the continuous and rapid advancement in technology, there may come a time when it will be possible for others to read and understand our thoughts. Although current research requires obtaining consent from subjects, it is possible that future research could be accomplished without a subject's permission. Macdonald[106] raised 2 important ethical questions in brain imaging: who should be able to observe our brain activity, and to what use such information be put? Meegan[107] highlighted scientific, ethical, and legal issues in neuroimaging techniques that included rights to privacy and against self-incrimination. Moreover, memory detection techniques still violate legal acceptability. We, therefore, foresee the fact that privacy issues will demand laws for the protection of an individual's thoughts.

In conclusion, in this article, we have reviewed the active roles of EEG and fMRI technology in human memory research. In particular, this study presented an overview of research on memory retention and recall processes in combination with available memory paradigms. Researchers have used memory paradigms to stimulate different brain regions in cognitive tasks for profound understanding of cortical and deep brain cognitive abilities. Analogous brain activation is reported in both EEG and fMRI studies. For retention and recall processes, frontal-central, frontal, occipital-parietal, prefrontal, hippocampus, bilateral hippocampal, and posterior parietal regions were all activated. We discussed some key issues and challenges in memory research related to EEG and fMRI techniques. We hope this review will provide useful insights for memory researchers.

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