Effect of Tactile Stimulation on Visual Memory Performance

By

Asma Latif

(Registration No: 00000400816)

Department of Biomedical Engineering and Sciences

School of Mechanical and Manufacturing Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2024)

Effect of Tactile Stimulation on Visual Memory Performance

By

Asma Latif

(Registration No: 00000400816)

A thesis submitted to the National University of Sciences and Technology, Islamabad,

in partial fulfillment of the requirements for the degree of

Master of Science in
Biomedical Engineering

Supervisor: Dr. Muhammad Nabeel Anwar

School of Mechanical and Manufacturing Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2024)

THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS/MPhil thesis written by **Regn No. 00000400816 Asma Latif** of **School of Mechanical & Manufacturing Engineering (SMME)** has been vetted by undersigned, found complete in all respects as per NUST Statues/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS/MPhil degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis titled. **Effect of Tactile Stimulation on Visual Memory Performance**

Signature:________

Name (Supervisor): Dr Muhammad Nabeel Anwar

Date: 24-12-2024

Signature (HOD):________

Date: 24-12-2024

Signature (DEAN):________

Date: 24-12-2024

Form TH-4

National University of Sciences & Technology (NUST)

MASTER'S THESIS WORK

We hereby recommend that the dissertation prepared under our supervision by: Asma Latif (00000400816)

Titled: Effect of Tactile Stimulation on Visual Memory Performance be accepted in partial fulfillment of the requirements for the award of MS in Biomedical Engineering degree.

Examination Committee Members

1.	Name: Muhammad Tauseef Nasir	Signature:
2.	Name: Ahmed Fuwad	Signature:
Supervisor: Muhammad Nabeel Anwar	Signature: Date: 20 - Dec - 2024	

	20 - Dec - 2024
Head of Department	Date

COUNTERSINGED

20 - Dec - 2024	
Date	Dean/Principal

CERTIFICATE OF APPROVAL

This is to certify that the research work presented in this thesis, entitled “Effect of Tactile Stimulation on Visual Memory Performance” was conducted by Ms Asma Latif under the supervision of Dr. Muhammad Nabeel Anwar.

No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the Department of Biomedical Engineering and Sciences in partial fulfillment of the requirements for the degree of Master of Science in Field of Biomedical Engineering.

Department of Biomedical Engineering and Sciences National University of Sciences and Technology, Islamabad.

Student Name: Asma Latif Signature: ________________

Supervisor Name: Dr. Muhammad Nabeel Anwar Signature: ________________

Name of Dean/HOD: Dr. Muhammad Asim Waris Signature:________________

AUTHOR'S DECLARATION

I Asma Latif hereby state that my MS thesis titled " Effect of Tactile Stimulation on Visual Memory Performance" is my own work and has not been submitted previously by me for taking any degree from National University of Sciences and Technology, Islamabad or anywhere else in the country/ world.

At any time if my statement is found to be incorrect even after I graduate, the university has the right to withdraw my MS degree.

Name of Student: Asma Latif

Date: 20-Dec-2024

PLAGIARISM UNDERTAKING

I solemnly declare that research work presented in the thesis titled "Effect of Tactile Stimulation on Visual Memory Performance" is solely my research work with no significant contribution from any other person. Small contribution/ help wherever taken has been duly acknowledged and that complete thesis has been written by me.

I understand the zero tolerance policy of the HEC and National University of Sciences and Technology (NUST), Islamabad towards plagiarism. Therefore, I as an author of the above titled thesis declare that no portion of my thesis has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled thesis even after award of MS degree, the University reserves the rights to withdraw/revoke my MS degree and that HEC and NUST, Islamabad has the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized thesis.

Student Signature: ______________________

Name: Asma Latif

To my loving parents, whose unwavering support and endless encouragement have been the foundation of my success.

To my supervisor and the extraordinary individuals who pursue their dreams with courage, inspiring me to achieve greatness.

ACKNOWLEDGEMENTS

First and foremost, I am deeply grateful to Allah (SWT), the Most Merciful and Compassionate, whose countless blessings, divine guidance, and infinite wisdom have given me strength and resilience throughout this academic journey.

I am profoundly thankful to my parents, Muhammad Latif and Razia Perveen, whose unwavering love, selfless sacrifices, and endless support have been the foundation of my success. Your confidence in me and constant prayers have been a source of strength that has guided me through every step of this journey.

I extend my heartfelt gratitude to my dear sisters, Fatima Latif and Rabia Latif, for their immense support and encouragement throughout this journey. Your unwavering presence and assistance have made everything more manageable and meaningful. A special mention goes to my beloved nephew, Muhammad Zaviyar Amir, whose joy have been a constant source of happiness.

I want to express my sincere appreciation to my supervisor, Dr. Muhammad Nabeel Anwar, for his invaluable mentorship, insightful guidance, and continuous encouragement throughout my research journey. I am equally grateful to my GEC members, Dr. Ahmed Fuwad and Dr. Muhammad Tauseef Nasir, for their thoughtful feedback and valuable contributions, which were pivotal in shaping my work.

I am also incredibly thankful to my amazing friends Omna Ashfaq, Ayeza Shahid, Sadaf Zahra, Atiqa Saeed and Mina Khalid for their unwavering support and countless memories we have created, from group studies to endless conversations and shared laughter, have been an integral part of this journey. I would like to express my gratitude to Ms. Natasha Shahzadi and Muhammad Hamza Khalil for rendering valuable assistance in my research work.

To all who have supported me along the way, thank you for being a part of this incredible journey.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

MMSE	Mini Mental State Examination
EHI	Edinburgh Handedness Inventory
STM	Short Term Memory
LTM	Long Term Memory
EEG	Electroencephalogram
PCB	Printed Circuit Board
RAVLT	Rey Auditory Verbal Learning Test
RAT	Remote Association Task
AUT	Alternative Uses Test
spTMS	Single-pulse Transcranial Magnetic Stimulation
PPC	Posterior Parietal Cortex
SI	Primary somatosensory Cortex
SII	Secondary somatosensory Cortex
DLPFC	Dorsolateral prefrontal cortex
MFG	Middle Frontal Gyrus
MWM	Morris Water Maze
WBV	Whole Body Vibration
VIN	Visual Network
SMN	Sensorimotor Network
ECoG	Electrocorticography
MEG	Magnetoencephalography

ABSTRACT

The human eye continuously perceives information about surroundings to be processed and stored in memory so that it can be retrieved. Environmental factors may have positive and negative effects on memory performance and human cognitive processing. Many studies have addressed the effect of auditory circumstances on spatial tasks and visual memory performance. However, only a few studies highlighted the cross-modal interaction between vision for visual cue and touch for training of same visual pattern in tactile pattern. In addition, very little research has been conducted on the effect of tactile stimulation towards memorizing visual tasks. The main objective of this study is to investigate the effect of visuo-tactile stimulation on adult memory. Sixty-two subjects participated in this behavioral study having normal and corrected to normal vision. Participants are divided into two groups and each subject goes thorough Mini mental state examination and Edinburg handedness inventory. The visual assessment task consists of different shapes along with three-digit numbers. During the memorization period, visual assessment task was displayed on computer screen and tactile stimulation was delivered on index finger of the dominant hand of the participant. The participant was provided with an evaluation sheet containing shapes only. If the shape is paired with its corresponding number, then it was be considered correct. The p-value < 0.05 in visual assessment test showed a significant effect of tactile stimulation on visual memory performance. The findings of this study concluded that participants memorized the object number pair task better in the presence of tactile stimulation as compared to control/no stimulation. One of the conclusions of our work is that combing vision and touch sense may improve cognitive ability and may be provided to people during learning and remembering visual tasks. For future recommendations, heterogenous sample along with brain response can be studied.

Keyword: Visual memory, tactile stimulation, Meissner and Pacinian Corpuscles, cross modal integration, tactile-visual sensory interaction.

CHAPTER 1: INTRODUCTION

1.1 Memory

Memory is an intellectual capacity that is necessary for processing and retaining information throughout time, enabling people to recollect knowledge, abilities, and experiences from the past. It is essential for education, making decisions, and preserving the identity of a person. We cannot learn new things or retain existing knowledge, remember past events, or simply carry out daily jobs if we do not have memory. The processes that make up memory are dynamic and include encoding, which is how we process information, storing it, which is how we keep it, and retrieval, which is how we catch it later [1]. This complex system is essential to unconscious behavior such as habits as well as conscious thought. Hence, memory serves as a key cognitive building block, influencing not just our thoughts but also our behaviors and perceptions of the outside world. It acts as a link among all three periods of time, enabling people to make plans, navigate their current surroundings, and draw lessons from their history.

1.2 Function of Memory

Memory is essential for learning, solving problems, and modifying behavior based on prior experiences, among other critical tasks. It makes it possible for people to collect information that they can use to successfully navigate their surroundings. We may create a picture of the world through memory and forecast future events based on the knowledge we have gained. It also plays a vital function for enabling us to identify and understand patterns, individuals, and objects. By allowing us to productively combine previously learned material in innovative ways, memory advances creativity.

Memory helps in physical skills, emotional reactions, and social interactions in addition to cognitive tasks [2]. The memory system is constantly updating and rearranging itself in response to new experiences, which increases its versatility. By relating experiences from the past to the present, memory also helps people to form a sense of self [3].

1.3 Stages for Memory Formation

The three main phases of memory are encoding, storing, and retrieval.

1.3.1 Encoding

The process of transforming sensory information into a format that the human brain can store is called encoding. Different techniques, like auditory, visual, or semantic processing, might be used in encoding. Better memory retention results from deep, meaningful encoding [4].

1.3.2 Storage

After the data has been encoded, it is placed there until it is required again. Long-term memory and short-term memory are two types of storage. While long-term memory can retain knowledge for days, many years, or perhaps a lifetime, short-term memory, sometimes referred to as working memory, only stores information momentarily, frequently for only a few seconds to minutes [5].

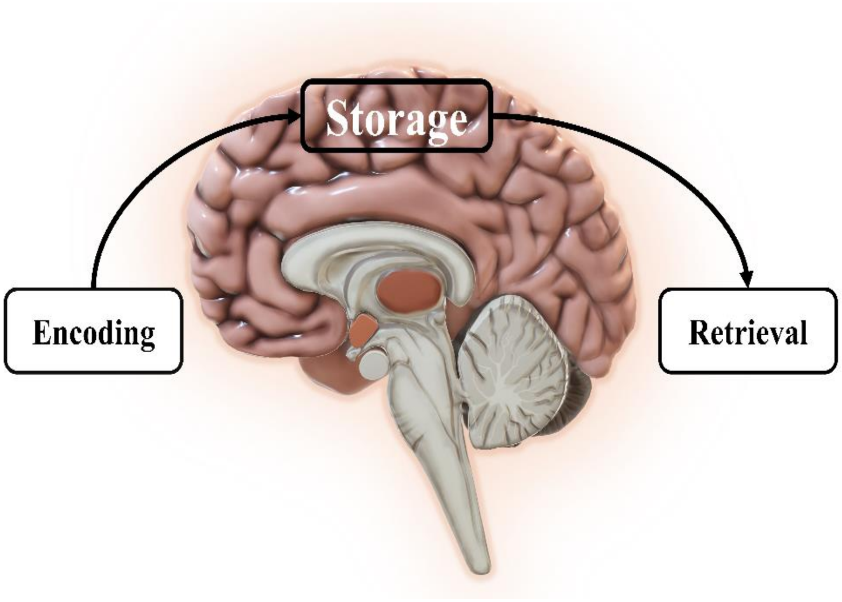


Figure 1: Stages of Memory Formation

1.3.3 Retrieval

Information that has been stored can be accessed via the process of retrieval. It might be forced, like remembering a strange incident, or automatic, like remembering a word. Information is often encoded in a context that affects memory retrieval [6].

1.4 Types of Memory

Based on the form and duration of information retention, memory can be divided into three types. These are named as Sensory memory, Short-term memory (STM), long-term memory (LTM). In the way that individuals organize, store, and retrieve information, each kind has a distinct function. Acquiring insight into these various memory types facilitates illuminating the cognitive mechanisms that underline learning and daily functioning [7].

1.4.1 Sensory Memory

The simplest and most immediate type of memory is sensory memory, which oversees retaining sensory information for a split second after the sensory input has stopped. It is the initial phase of memory processing, holding onto environmental information long enough for short-term memory to absorb it. Before they disappear or undergo additional processing, sensory memories enable us to temporarily record and integrate visual, aural, and tactile experiences [8] [9].

Iconic memory

Depending on the sense mode used, there are various kinds of sensory memory: Visuals sensory memory known as "iconic memory" has a duration of roughly 200-500 milliseconds. It facilitates seamless visual perception by enabling people to temporarily retain an impression of what they recently saw. For instance, even if the images in movies are fast-flashing static frames, the feeling of motion is made possible by iconic memory [10].

Echoic Memory

This type of sensory memory is aural and lasts for two to four seconds. It helps people retain and interpret words that are spoken or other sounds, so even if the listeners focus momentarily turns, the brain can still understand spoken language [11].

Haptic Memory

The touch sensory memory is known as haptic memory. Similar to iconic and echoic memories, tactile information is momentarily stored in haptic memory before disappearing [12].

1.4.2 Short Term Memory (STM)

Information is only stored in short-term memory (STM) for a brief period, usually between 20 and 30 seconds, provided it is actively practiced or sustained by repetition [13]. Additionally, STM can only handle roughly 7±2 objects at once [14]. When engaged in active information manipulation, including problem solving, mental math, or understanding complicated phrases, it is commonly referred by the term working memory.

If short-term memory contents are not moved to long-term memory, they may quickly deteriorate. For instance, when someone searches for a phone number, they tend to forget it quickly unless they practice it frequently. For routine cognitive processes like reasoning, comprehension, and picking up new knowledge, short-term memory is essential.

Acting as a buffer between sensory memory and LTM is one of STM key roles. STM quickly stores information while we focus on sensory stimulation, which is then transferred to long-term memory by encoding or rehearsal [5].

1.4.3 Long Term Memory (LTM)

Information is stored in long-term memory (LTM) for periods ranging from a few minutes to a lifespan. Long-lasting memory has a virtually infinite capacity, in contrast to memory that is short-term, which has limited storage space and durability. Information in LTM is arranged to make retrieval easier when needed and can be stored indefinitely.

The long-term memory is further divided into two types that are:

Declarative Memory

Declarative memory, which includes episodic memory for events and semantic memory for knowledge, is the kind of memory that entails deliberately recalling facts and occurrences. It is essential for routine memory processes including recognition and recalling prior events [15].

Non-Declarative Memory:

Implicit memory, also known as non-declarative memory, is a kind of long-term memory that operates subconsciously. It enables people to execute abilities or activities automatically, without conscious memory. This memory functions without conscious awareness and is formed via repetition or practice [16].

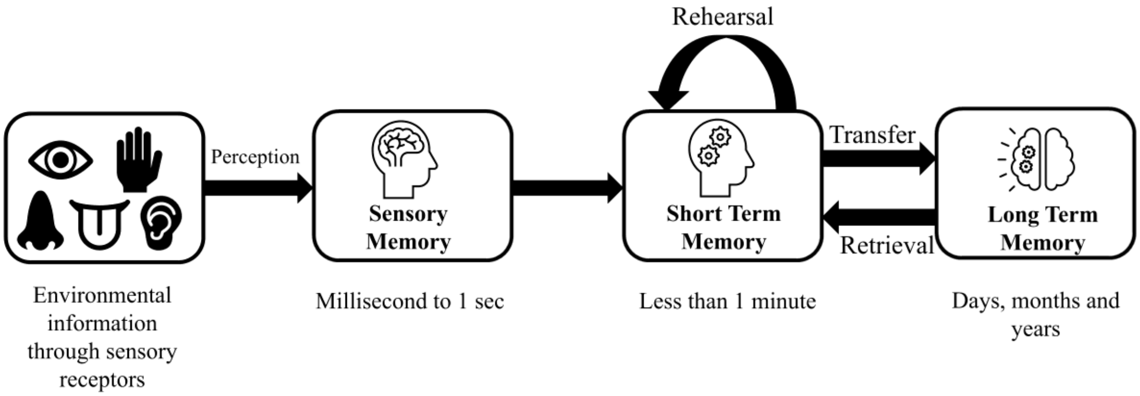


Figure 2: Types of Memory

1.5 Visual Memory

The ability to precisely encode, store, and recover visual information such as pictures, forms, colors, and spatial relationships is referred to as visual memory performance. To preserve and retrieve visual stimuli from short-term memory and long-term memory, it entails the mental processing of visual input. Excellent visual memory performance is essential for tasks requiring visual recall because it allows people to effectively recall and manipulate visual cues, objects, or settings they have seen.

1.5.1 Function of Visual Memory

Visual memory plays a vital role in education because it helps learners retain the shapes of numbers, letters, and symbols, all of which are essential for writing, reading, and math. For remembering textbook diagrams, graphs, and illustrations, students rely on visual memory. It is particularly basic for visual pupils to retain knowledge and assimilate complex material.

The capacity to ignore distractions and concentrate on essential visual information is supported by an effective visual memory. This is crucial in settings involving plenty of visual information, such crowded streets or offices, where you must focus on significant details and retain important visual cues.

Activities involving hand-eye coordination, including driving, playing an instrument, or participating in sports, benefit from visual memory. In tasks requiring physical coordination, the ability to recall visual cues facilitates fluid movement execution and guarantees correctness and precision.

1.6 Tactile Stimulation

In this research we used tactile stimulation in the form of vibration instead of auditory stimulation. The reason is that past researches have studied the impact of auditory white noise on visual memory, but a few studies investigate the effect tactile stimulation. The introduction of this new sensory stimulation helps us in understanding cross modal integration between touch and vision.

Meissner and Pacinian corpuscles function as specialized mechanoreceptors in the complex field of human sensory experience. They are specially tuned to detect vibrations of specific frequency that interact with the skin. The epidermal and subcutaneous layers contain these corpuscles, which are essential to the haptic feedback system that provides the brain with environmental information.

1.6.1 Meissner Corpuscles

Meissner corpuscles are extremely responsive to vibrations of low frequencies 10 to 50 Hz, which are frequently associated with soft touches and fine textures as fingertips brushing or a gentle breeze [17]. They are on the surface dermal papillae of hairless skin. For sensitive tasks like reading Braille or perceiving small surface details, they are crucial because when they are active, they immediately convey signals to the brain that are usually considered pleasant and soothing.

1.6.2 Pacinian Corpuscles

Pacinian corpuscles, on the other hand, are designed to detect high-frequency vibrations, usually in the range of 80 to 450 Hz, with a sensitivity peak value of 250 Hz [18]. These receptors are more deeply buried in the dermis and subcutaneous tissue. They respond very well to sudden, strong vibrations but are less sensitive to mild touch. Mid-range high-frequency vibrations, which fall between 80 and 300 Hz, are commonly described as both energizing and pleasurable. This experience is akin to that of a well-tuned engine or a vibrating massager.

The ideal condition for storing and retrieving visual information may be created by low-frequency vibrations, which are frequently calming and may help lower anxiety and increase focus. High-frequency vibrations, on the other hand, are more stimulating and may help with learning by enhancing alertness and attention. This is particularly helpful when it comes to sustaining interest in activities that call for prolonged focus.

1.7 Multisensory Integration

The process by which the brain integrates data from several sensory modalities such as hearing, vision, and touch to produce a coherent view of the outside world is known as multisensory integration. This idea is intriguing for improving cognitive processes including attention, recall, memory, and learning when it comes to sensory input in the form of vibrations and its impact on visual memory performance.

1.7.1 Cross Modal Integration between Visual and Touch Sense

Certain skin sensory receptors are triggered by vibration as a haptic stimulus, and these receptors transmit information to the somatosensory cortex, the part of the brain that processes touch. These vibrations can affect alertness or arousal levels, which directly affect cognitive processes like memory. Arousal enhances the capacity to encode and recall information by increasing attentional resources. The occipital lobe and portions of the temporal lobe of the brain especially the hippocampus, which is essential for long-term memory [19] usually process visual memory.

Information from various senses is processed collectively by the brain's multisensory regions, such as the parietal cortex or the superior colliculus. By interacting with visual processing systems, vibration-based tactile stimulation can improve the connection between the visual memory task and the sensory experience. Memory retention of visual information may be improved by rhythmic vibrations that synchronize with the brain's natural oscillations such as theta waves associated with memory processing, particularly in the hippocampus [20].

1.8 Problem Statement and Contribution

Differences in cognitive performance, involving deficits in memory recall and retention, can result from changing experiences. Memory processing problems can be a contributing factor to a number of cognitive and psychiatric disorders. Most of the time, poor memory function might interfere with daily tasks, resulting in lower cognitive performance and higher stress levels. By encouraging multimodal integration that supports memory storage and retrieval, tactile stimulation, especially rhythmic vibrations; is thought to improve visual memory performance.

1.9 Aims and Objectives

Some studies suggest that various forms of auditory stimulation may serve as a non-pharmacological approach to enhance visual memory performance. There is a need to test the effect of other sense like touch on memory. The degree of improvement by utilizing reliable, large-scale data collection and analysis tools is required for this study. There are the following objectives of this study:

1. To exam the effect of tactile stimulation on visual memory.
2. To assess whether tactile stimulation can be a non-pharmacological treatment for improving memory performance.
3. To check whether the low or high frequency vibration has a positive or negative impact on visual memory.
4. To assess which frequency vibrations are either low or high is more effective.
5. To check the different order or sequence of tactile stimulation effect differently the memory performance.

Unlike previous studies, we used tactile stimulation over auditory stimulation along with behavioral assessment.

CHAPTER 2: LITERATURE REVIEW

2.1 Effect of Tactile Stimulation on Memory Performance

Psychological research has shown interest in the relationship between tactile stimulus and cognitive processes including memory and creativity. Using the Rey Auditory Verbal Learning Test (RAVLT) as the main memory performance test, this study examines how involuntary tactile stimulation affects creativity of young adults and Rey Auditory-Verbal Memory [21]. Over the course of five trials, participants are required to remember a list of fifteen words. To evaluate proactive interference, another list of words is shown. To test retention and forgetting rates, subjects are asked to recollect the original list once more after a certain amount of time. Experimental group has 30 minutes tactile stimulation on index finger while in control group no stimulation is provided. According to this study, involuntary tactile input can have a good impact on young adults' memory and some forms of creative thinking. It specifically improves memory for words and convergent creative thinking while having no effect on divergent creativity.

Figure 3: Tactile Stimulation device by Mahan Sanat-Kavosh Pars Co.

Numerous research has examined the effects of pressure as a tactile stimulus on working memory, with an emphasis on the ways in which tactile sensations can affect cognitive functions in healthy people. Twenty-four healthy individuals (12 women and 12 men) participated in the study. Participants applied tactile pressure on the left thumbnail while performing a verbal n-back assignment (0-back and 2-back). When comparison to the 0-back test, performance of the participants during the 2-back task was noticeably worse, suggesting that more complicated tasks require more cognitive burden. Interestingly, performance in the two tasks was unaffected by the amount of tactile pressure used, indicating that working memory outcomes were not much impacted by low-salient tactile stimuli [22]. The function of frontoparietal networks in visual working memory was confirmed by fMRI data, which showed predicted activation patterns. Higher cognitive demands were mirrored in increased activity of the dorsolateral prefrontal cortex (DLPFC) and middle frontal gyrus (MFG). Furthermore, in line with their functions in somatosensory processing, tactile stimuli elicited activation in the parietal operculum (SII) and postcentral gyrus (SI). However, there was no discernible relationship between working memory load and tactile pressure, indicating that cognitive load had no effect on cross-modal processes, which is consistent with concepts of automaticity in the processing of sensory information. These results demonstrate how tactile and visual information processing can function independently under different task demands.

In a haptic orientation sequence task, participants used their fingers to detect sequences. To evaluate accuracy and memory recall, each trial included a sample sequence and a test sequence. Following nine days of instruction, participant's performance on visuospatial task and visual orientation sessions sequence task showed significant gains. This implies that without practicing visual tasks directly, tactile training can improve visual working memory [23]. Following training, the accuracy rates tactile orientation task dramatically progressed, suggesting that the tactile input improved cognitive processes associated with visual memory tasks.

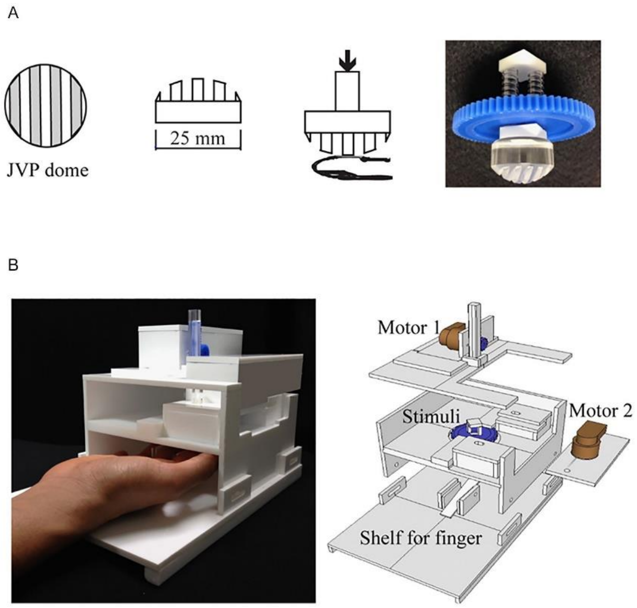


Figure 4: Tactile Grating Training Device and Setup

According to the study, tactile stimulation greatly improves rat's spatial memory function. When tactile stimulation is given during crucial developmental stages, this improvement is especially noticeable, indicating a vulnerable window for successful intervention. Additionally, the study discovered that the number of neurons in the hippocampus (a part of the brain essential for memory and spatial navigation) is positively impacted by tactile stimulation. Better spatial memory ability is correlated with increased neuronal density, suggesting a possible neurobiological explanation behind the noted cognitive advantages [24].

The study discovered that the number of events given in the task-irrelevant medium had a significant impact on the perception of a number of activities in one modality. In particular, visual perception was more strongly influenced by tactile stimuli than the other way around. Because participants gave fewer variable predictions when response to tactile stimuli alone, touch was found to be a more trustworthy sensory modality than vision. Perceptual assessments were less erratic as modalities were shown simultaneously than when they were shown separately. This implies that the brain tends to immediately integrate info from both modalities, even if one sensory input is deemed irrelevant [25].

2.2 Effect of low and high frequency vibration on memory

30 Hz vibration for 5 Week for 1 h each day on 18-month-old rats. Aged Wistar rats that received a 5-week WBV intervention showed improved spatial memory and motor performance. Several cognitive tests were used to evaluate this, such as the novel position recognition test, which showed that rats treated with WBV had improved memory retention in comparison to control groups that received pseudo-vibration treatments. During open field testing, rats who received 20-minute daily sessions demonstrated markedly reduced anxiety, as seen by improved rearing behavior and reduced immobility. Although the lengthier sessions were more successful in lowering anxiety levels, the outcomes were dependent on dose, with both 5- and 20-minute sessions yielding positive results [26]. The experimental protocol used in this study is shown in the figure below:

Figure 5: Whole Body Vibration delivering Device for Rats

The observer's capacity to distinguish between different visual orientations was impaired when their index finger vibrated tactilely. The activation of visuo-touch bimodal neurons in regions like the ventral intraparietal area indicates that these neurons react both to tactile and visual stimuli. This makes it possible to inhibit visual perception when tactile input is present. Tactile stimulation was concurrently applied for 200 ms. Tactile stimuli were presented through an audio interface and a vibrator. In order to mask the sounds emitted by the vibrator, white noise bursts were generated digitally and delivered through headphones [27].

In mice models, a study showed that 40 Hz vibrations of low frequency could lower vital markers of Alzheimer's disease, such as phosphorylated tau. When compared to untreated controls, mice given this stimulation for an hour every day for a few weeks showed improvements in both neural health and motor function. It has been demonstrated that vibrotactile stimulation increases neuronal activity in key brain areas, including the primary motor cortex and primary somatosensory cortex. Tau P301S and CK-p25, two distinct mice models, showed reduced brain disease and neurodegeneration as a result of this stimulation. The mechanism for delivering tactile stimulation used in this study [28] is shown in figure below:

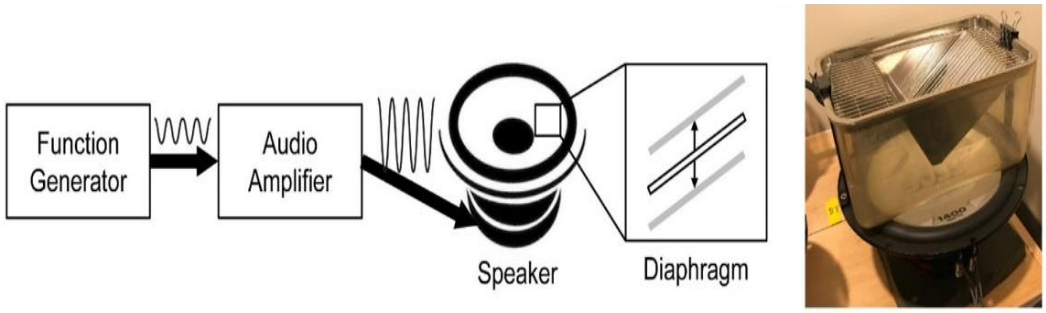


Figure 6: Tactile Whole Body Vibration using Speaker

Research has indicated that 40 Hz vibrotactile stimulation reduces brain disease in mouse models of neurodegeneration by increasing neural activity in important brain regions such as the primary motor cortex and primary somatosensory cortex [28]. According to a recent scoping review, haptic low frequency vibration has the potential to be an effective intervention for controlling the symptoms of dementia, especially in improving cognitive performance and lowering behavioral problems [29].

When given tactile stimulation during pregnancy, anxious rats perform better on spatial learning tasks like the Morris Water Maze (MWM). In contrast to their non-stimulated opponents, these rats showed reduced escape latencies, suggesting improved spatial learning skills. Additionally, tactile stimulation seems to restore the hyperactive adrenal activity that is commonly seen during cognitive activities in rats under prenatal stress. Following MWM training, corticosterone hormone levels in these rats were like those in control groups. Male and female rats may respond differently to tactile stimulation in terms of neurogenesis and cognitive function; certain results suggest that female rats benefited from higher dentate gyrus cell survival after tactile stimulation, whereas male rats demonstrated increases in cognitive function without appreciable changes in cell survival [30].

2.3 Internal brain circuits engaged in tactile situation and memory

The study discovered that the right inferior parietal cortex and bilateral anterior insula were active after 8 seconds of delayed vibrotactile frequency discrimination, suggesting that these regions are involved in working memory tasks. The right anterior insula, bilateral posterior parietal cortex, and right middle temporal gyrus all showed substantial stimulation when participants were distracted [31]. Compared to earlier research in the visual or auditory domains, the findings provide new evidence in the setting of vibrotactile stimuli that both attention and working memory possess partially overlapping brain circuits. The study employed vibrotactile stimulation with a frequency of about 25 Hz. Meissner's corpuscles, sensitive mechanoreceptors found in the dermal-epidermal interface of the outer glabrous skin, are the main reason this frequency was chosen.

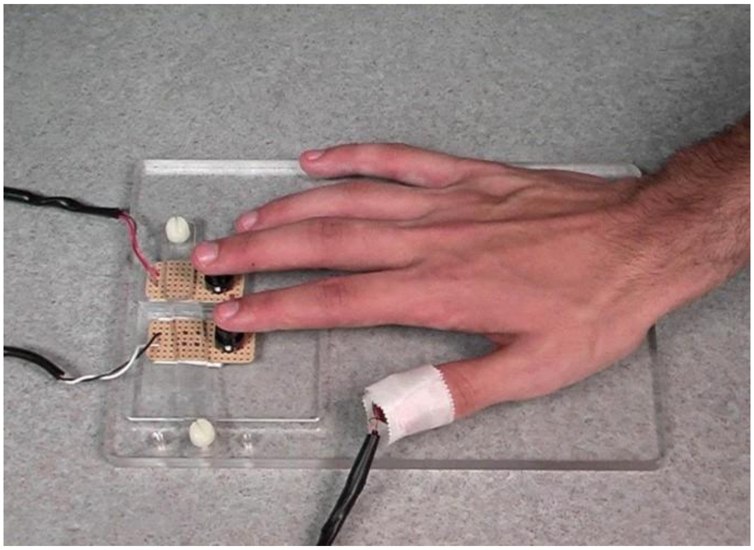


Figure 7: Magneto-mechanical Vibrotactile Device

This study [32] identifies certain neural patterns linked to various vibrotactile frequencies, shedding light on how the brain interprets and remembers them during working memory tasks. The main somatosensory cortex was shown to have steady-state evoked potentials that were synced with stimulus frequency, suggesting that it plays a part in processing touch information. Frequency-dependent alpha-band responses were observed in nonprimary cortical areas, especially the dorsal occipital cortex, indicating that various oscillatory patterns are engaged by different frequencies. Beta activity across the prefrontal cortex, particularly in the frontal gyrus that is inferior, was regulated in accordance with the frequency stored in memory throughout the retention phase, underscoring its significance in preserving frequency information for effective discrimination. For the purpose of subsequent frequency discrimination, vibrotactile stimuli with frequencies ranging from 16 to 41 Hz were administered at the left index finger.

In rats under prenatal stress, postnatal tactile stimulation from birth to maturity increases neurogenesis in the hippocampus dentate gyrus. The detrimental effects of stress during pregnancy, which generally lowers the proliferation of hippocampus granular cells, are offset by this stimulation, which increases the survival and development of new neurons. Early-life interventions may have long-lasting effects on the structure and function of the brain since the beneficial effects of stimulation by touch on neurogenesis seem to endure into adulthood. In particular, research [30] suggests that by boosting the number of new cells in the dentate gyrus, prolonged tactile stimulation can avoid learning impairments linked to fetal stress.

2.4 Brain network responsible for perception of vibrotactile stimulation and visual memory

The study discovered that in response to various vibrotactile frequencies, both the main somatosensory cortex and the secondary somatosensory cortex display high-gamma activities. The researchers discovered that the primary and secondary somatosensory cortices high-gamma activity (50-140 Hz) reacted differently to different vibrotactile frequencies using electrocorticography (ECoG). Different temporal patterns between SI and SII are highlighted in the study. In response to vibration stimuli, SI displays short-delayed high gamma power peaks (50–100 ms) that rapidly diminish, but SII displays a longer arousal (150–250 ms) that rises with increasing stimulus frequencies. This implies that SII is essential for processing high-frequency vibrations, whereas SI is more involved in the first phases of vibrotactile processing. They found that SII had longer sustained activity at higher frequencies, whereas S1 displayed more transitory responses. This suggests that SII is essential for processing prolonged high-frequency inputs in touch perception [33].

The study [34] investigated how the brain somatosensory cortex processes vibrotactile impulses at various frequencies. The study investigated how the index finger responded to a range of vibrations (20–200 Hz) using fMRI. They found that in the secondary somatosensory cortex, as opposed to the primary somatosensory cortex, higher frequencies activate more frequency-dependent voxels, especially in the lateral sulcus region. Around 50 Hz, which is the threshold frequency that distinguishes vibration sensations from flutter, this divergence was more noticeable. The results point to potential function of SII in distinguishing between high- and low-frequency tactile input by suggesting that it may include specific neuronal assemblies for processing different tactile frequencies.

Magnetoencephalography (MEG) was used to examine how the brain reacts to high-frequency tactile stimulation. In a sample of right-handed participants, researchers [35] applied 150 Hz vibrations to both index fingers of the hand. They discovered different neural responses. Notably, the contralateral primary sensorimotor cortex had the strongest M50 and M100 responses, which occurred approximately 56 and 100ms after the stimulus and indicated early, strong somatosensory interpretation of high-frequency vibrations. Furthermore, the study found that these vibrations significantly suppressed the alpha and beta frequency bands (8–12 Hz and 20–30 Hz, respectively), particularly in the sensorimotor regions. For the non-dominant hand, the suppression was more extensive and noticeable, indicating subtle lateralization effect in somatosensory processing. This study adds to our understanding of how tactile stimuli are encoded in the brain's sensory areas by highlighting the ways in which high-frequency vibrations activate the somatosensory system and proposing different processing patterns depending on handedness.

This study by Seth Koenig [36] investigates the role that the hippocampus plays in relational memory, which is the capacity to remember relationships between disparate types of information, such as object-location pairings. According to the study, networks that combine spatial, context-specific and temporal elements are crucial to the formation and retrieval of these associative memories in the hippocampus. Relational memory is severely hampered by hippocampal damage, demonstrating the hippocampal region critical role in structuring intricate, interconnected events and supporting adaptive behavior rooted in prior encounters.

Jordana S. Wynn and colleagues [37] investigated the relationship between eye movements and brain activity in memory retrieval. The study focused on "gaze reinstatement," in which participants recalled a sight or image by repeating their initial eye movements. Successful memory recall was highly correlated with this restoration of gaze patterns, indicating that eye movements had a role in the processing and retrieval of memories. According to the study, the para hippocampal area and the occipital pole, two brain regions involved in oculomotor control and visual processing exhibit activity patterns that forecast gaze reinstatement. Neural patterns associated with gaze reinstatement during recall of memories were also observed in the hippocampus, which is well-known for its function in memory formation. The "scanpath theory," which postulates that eye movements during acquisition of information aid in the storage of high-level visual information and that these motions are replayed to improve memory during retrieval, is supported by these findings.

A study [38] investigated the relationship between coordinated eye movements and brain activity during episodic memory development. According to the study, certain cortical oscillations that facilitate memory storage are correlated with eye movements, especially saccades, which are quick changes in gaze. It has been demonstrated that this connection between ocular movement and cortical brain rhythms improves the development of episodic memories by coordinating the brain processing with important visual information at critical times. The study also showed that the brain's method for prioritizing and processing visual information that is important for subsequent recall is reflected in this cortico-ocular synchronization, which may help with the selection and storing of memory-relevant information during learning sessions.

2.5 Brain network responsible for cross modal integration

The multisensory integration network in brain, which is essential for integrating touch and visual cues to improve memory storage. As they attempt to combine sensory inputs like touch and sight into a coherent experience, the posterior parietal cortex and insular cortex are especially involved in this process. Through the efficient integration of these inputs, this network enhances the development of more robust and rich memory representations. By directing attention toward several sensory inputs, the superior colliculus helps to improve the focus required for efficient memory storage. A smooth multimodal experience that enables both instant perception and a longer-term memory consolidation is made possible by the intricate interaction between touch and visual signals made possible by these regions working together. This integrated network demonstrates how coordinated sensory inputs might improve cognitive function, particularly while performing activities that call for memory retrieval and retention.

This study [39] examines oscillatory activity in several frequency bands throughout a visual and tactile pattern-matching test to learn more about how the brain combines touch and visual information. For numerous sensory inputs to generate coherent impressions, this kind of integration is essential. The parietal, prefrontal, and superior temporal cortex are important brain areas that are involved in this process. The brain can successfully integrate sensory inputs from many modalities thanks to the superior temporal cortex, which is crucial for integrating auditory and multisensory information. Combining tactile and visual signals to produce a cohesive perceptual experience is made possible by the parietal cortex, this area well-known for its function in spatial perception and sensory integration.

Ku et al. [40] used single-pulse transcranial magnetic stimulation (spTMS) to examine the functions of the posterior parietal cortex (PPC) and primary somatosensory cortex

(SI) in tactile-visual cross-modal working memory. They put out a sequential paradigm in which PPC's function in integrating and preserving information across modalities comes after SI's processing of tactile inputs. The study, which used spTMS at various periods, revealed a hierarchical processing pattern in tactile-visual working memory, with early disruption of SI affecting task performance and later activation of PPC affecting memory retention.

Paper	**Subjects**	**Tasks**	**Tactile Stimulation**	**Study on**	**Findings**
[21]	92 right-handed participants	RAVLT RAT AUT	30 minutes Involuntary tactile stimulation	Human	Positive impact on verbal memory and convergent creativity
[22]	24 subjects right-handed participants	n-back task	Tactile stimulation in the form of low salient pressure on left thumbnail.	Human	Performance during 2-back task was worse
[23]	32 Participants	Visual orientation sequence task	9-day training of tactile orientation sequence task	Human	Positive impact on cognitive processing
[24]	4 groups of rats	8-arm radial maze test	Tactile stimulation with the help of soft brush	Rats	Improve spatial memory performance and increase neural density in hippocampus
[28]	Mouse with Alzheimer’s disease		40 Hz vibration for 1 h in the cage in which the mouse is placed.	Mouse	40 Hz tactile stimulation is a therapeutic treatment for Alzheimer’s disease.
[31]	12 right-handed	Forced-choice vibrotactile	25 Hz frequency vibrations on right	Human	The somatomotor

	subjects	frequency discrimination task	thumb		system and polymodal regions in the frontal, parietal, and insular regions are among the neural circuits are activated in response
[33]		Electrocorticography (ECoG) used to record brain activity	Flutter Frequencies 5, 20 and 35 Hz Vibration frequencies of 100, 250 and 400 Hz for 1s with inter-stimulus interval of 2.5, 3 and 3.5s	Human	Vibrotactile perception requires cooperation between the SI and SII regions, with SII important to process high-frequency vibrations
[35]	30 right-handed participants	Magnetoencephalography (MEG) to investigate neuromagnetic brain response to high frequency vibration	Sinusoidal vibration of 150 Hz for 200 ms on tip of index finger of dominant and non-dominant hand	Human	Elicit M50 and M100 responses and modulate alpha and beta oscillations in response of HFV
[34]	9 right-handed participants	Functional magnetic resonance imaging (fMRI) to investigate brain response	20-200 Hz vibration with 20 Hz increment on tip of index finger for 30 s with rest of 30 s	Human	Flutter frequency activated contralateral SI and bilateral SII while vibrational frequency activated bilateral SII

Table 1: Summary of Studies on Vibrotactile Stimulation and Visual Memory

CHAPTER 3: MATERIALS AND METHODS

3.1 Study Protocol

The study protocol used in this research is described below.

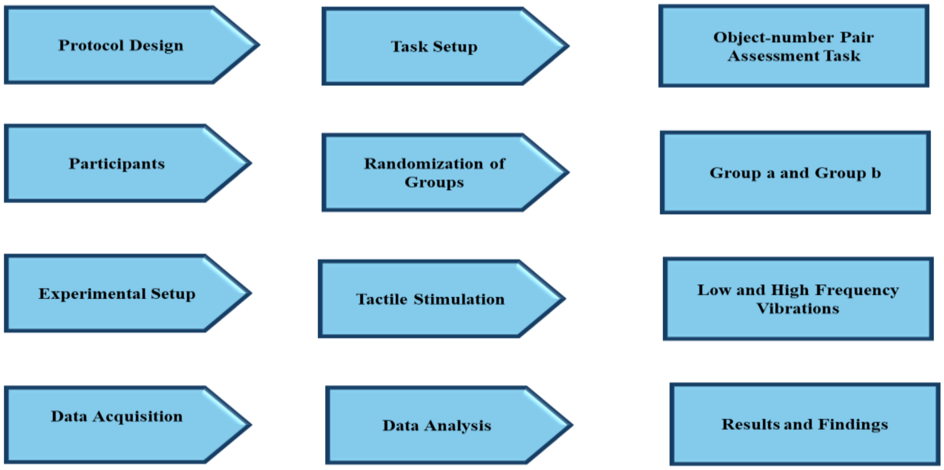


Figure 8: Study protocol

3.2 Software and Hardware

There following software and hardware are used in this research study for data acquisition and statistical analysis:

Software	Hardware	Data acquisition and statistical analysis
• Arduino • YouCut-Video Editor • MATLAB R2024a	• Laptop • Tactile stimulation device	• Evaluation Sheet • Psychomotor vigilance Task • Statistica

3.3 Materials

There are the following materials used in this study:

- Tactile stimulation device
- Display System
- Circuit Diagram

3.3.1 Tactile stimulation device

An Arduino UNO microcontroller, a mini mobile vibration motor, with a potentiometer to regulate the stimulation frequency were used in this study to create a unique tactile stimulation device. The main controller, the Arduino UNO, precisely controls the vibration patterns of the motor. The tiny vibration motor, which is frequently seen in mobile phones, was selected because of its small size and ability to provide tactile feedback. A potentiometer, which enables real-time adjustment of the voltage provided to the motor, was included to change the stimulation frequency. By efficiently modulating the motor's frequency, this voltage control allows for customized vibration intensities during testing.

This device is appropriate for investigating the impact of different tactile frequencies on participant’s visual memory performance because it provides targeted and customizable tactile stimulation. The ease of use and versatility of this tool also make it an affordable option for directed sensory stimulation research.

There are the following materials used in the construction of this device:

- Arduino UNO
- Vero Board
- Mini Mobile Vibration Motor
- Potentiometer

- Jumper wires
- Resistors
- Box
- TOPK Velcro Cable Organizer

Arduino UNO

The ATmega328P serves as the foundation for the Arduino UNO microcontroller board. It features a ceramic resonator operating at 16 MHz, 6 analog inputs, 14 pins for digital input and output (six of which can be utilized as PWM outputs), a USB port, a power port, an ICSP header, and a reset button. Everything required to operate the microcontroller is included; to get started, just use a USB cable for connecting it to a computer or power it with a battery or AC-to-DC adapter.

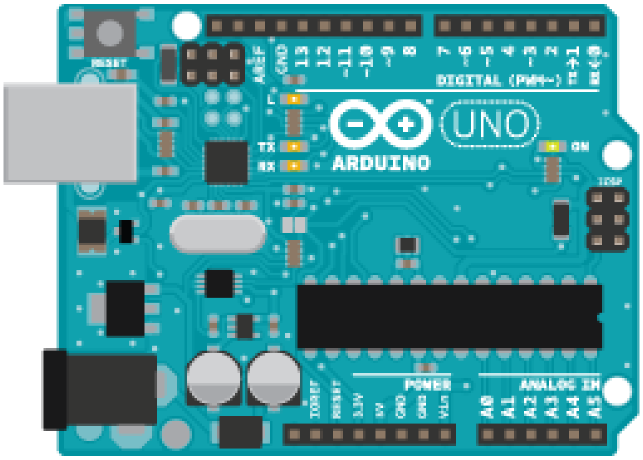


Figure 9: Arduino UNO Board

Vero Board

Similar to a printed circuit board (PCB), Vero board is a versatile prototyping board with a lot of tiny slots and copper dots. You may construct circuits and solder components onto it thanks to these holes. Wires can be used to route in whatever direction you want. Additionally, spring terminals on breadboards make it simple to connect wires and build circuits. Soldering is not required on breadboards. Compared to breadboards, printed circuit panels are more robust and adaptable. PCBs can carry higher currents than breadboards. Unlike breadboards, they may additionally be used for external connection. Additionally, compared to breadboards, printed circuit boards appear neater and more polished.

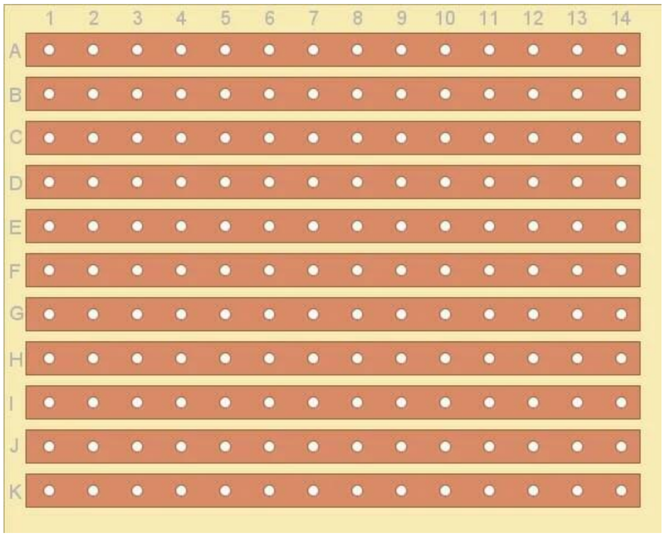


Figure 10: Vero Board

Mini Mobile Vibration Motor

The coin shaped flat vibration motor is a lightweight, tiny, and effective motor that produces modest vibrations. This flat motor has an eccentric mass, or tiny offset weight, that rotates quickly when power is given, in contrast to conventional motors with a revolving shaft. By constantly shifting the motor's center of gravity, the rotating motion of this off-centered mass produces vibration, which is quite noticeable when it comes into contact with the skin. Coin-type motors are perfect for placement on smaller locations, like the fingertip, avoiding discomfort or tiredness because they are usually quite thin and weigh just about 0.9 grams. For sensory investigations or tactile feedback systems, the motor's flat shape allows it to be firmly affixed to the fingertip, producing isolated and focused vibration.

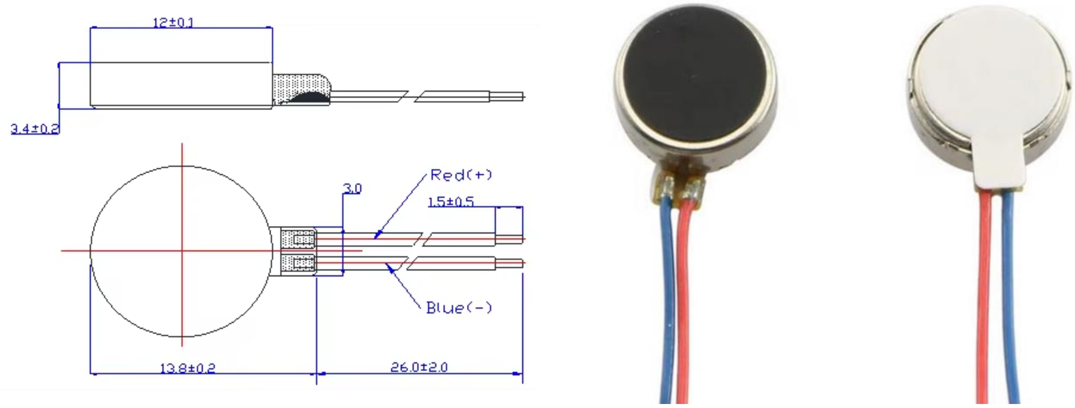


Figure 11: Mini Mobile Vibration Motor

The motor uses less power when operating at low voltages, which makes it appropriate for battery-powered systems. For controlled tests on sensory input or tactile perception, accurate and personalized tactile stimulation is possible with the capacity to modify the motor's frequency by varying the voltage. There are the following specifications of motor used in this study:

Specification	Details
Enclosure	Completely Enclosed
Speed (RPM)	16000 ± 2000 rpm
Proficiency	IE 2
Voltage Range	2.5~3.4V DC
Rated Voltage	3.0V DC
Rotation Direction	CW/CWW

Temperature Range	-10℃ to 60℃ (≤ 60% RH)
Rated Speed	16000 ± 2000 rpm/min
Stall Current	≤ 110 Ma
Rated Current	≤ 95 Ma
Starting Voltage	0.8V DC
Weight	About 0.9 g
Thickness	2.1 ± 0.1 mm

Table 2: Specifications of Mobile Vibration Motor

Potentiometer

Potentiometers are frequently used to regulate electrical equipment, including audio equipment volume controls. It is also employed in fan speed control. For instance, with a joystick, potentiometers that are controlled by a mechanism can serve as position transducers.

The fundamental working concept of a potentiometer is based on the observation that the potential across any given length of wire is precisely proportional to the wire's uniform cross-sectional area and continuous current flow. By modifying the circuit's resistance, a 1kΩ potentiometer gives control for modulating the voltage that motors and other components receive. This allows the vibration strength of motor to be precisely adjusted by varying the current flow.

Figure 12: Potentiometer

Jumper Wires

Jumper wire is in three different shapes: male-to-male, female-to-female, and female-to-female. It has a submerged female end and an outstanding point on one end, which is why we name it male-to-female. When it's male-to-male, both ends are male, and when it's female-to-female, both endpoints are female.

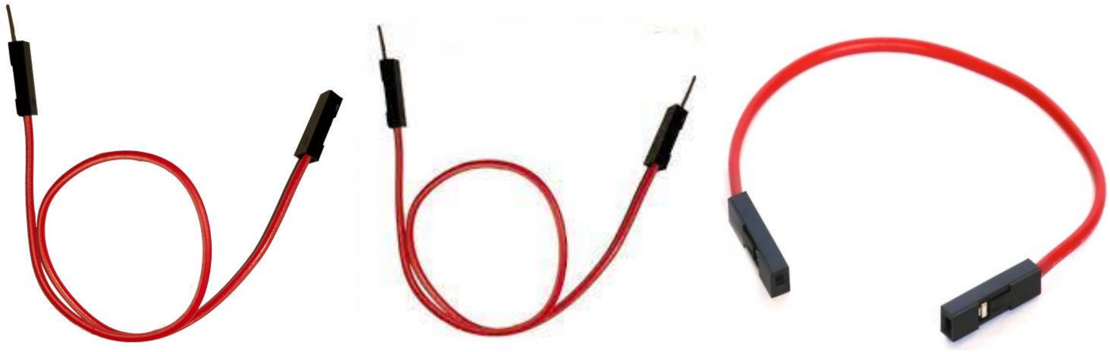


Figure 13: Jumper Wires

Resistors

A two-terminal passive electrical component used in electrical circuits to either limit or control the flow of electric current is basically called resistor. The primary function of resistor is to mitigate the voltage and current flow in a specific area of the circuit. The resistor dissipates a portion of the current energy as heat, which lowers the overall current. A 33 ohm resistor is used in design of the setup.

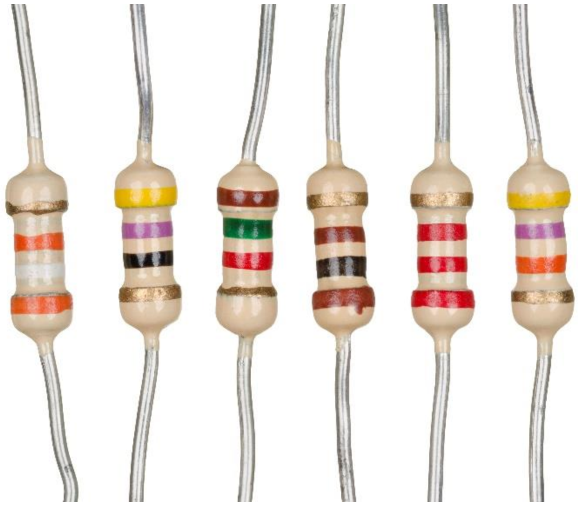


Figure 14: Resistors

Transparent Box

To construct a compact setup, a clear plastic box that is just a little bit bigger than an Arduino and breadboard is used. Attach both parts firmly within using screws or double-sided tape. Use short jumper wires or custom-cut wires to keep wiring neat and short. To provide access without taking the Arduino out, drill holes for the USB and other ports. Include a few tiny air holes if heat is an issue. This arrangement gives the project a polished appearance, organization, and portability.

Figure 15: Transparent Box

TOPK Velcro Cable Organizer

The Velcro cable organizer helps with easy adjustment and secure closure is made possible by the hook-and-loop Velcro fastening on this sturdy, flexible nylon garment. It is used to place the mini mobile vibration motor on the fingertip so that the motor should not misplace while it’s vibrating.

Figure 16: TOPK Velcro Cable Organizer

3.3.2 Display System

In this project design, a single laptop does two tasks: it powers the Arduino via USB and displays visual stimuli like animations or data visualizations. With the laptop handling both the power supply and visual output at the same time, this dual-purpose strategy guarantees effective resource use. The configuration stays small and simple, removing the need for extra gear and allowing for smooth control of both power and graphics from a single device.

Figure 17: Display system

3.3.3 Circuit Diagram

This circuit connects an Arduino Uno to a potentiometer and a vibration motor on a breadboard. The potentiometer is used to control the vibration frequency of the motor. It has three pins: one connected to the 5V power supply from the Arduino, one connected to ground (GND), and the middle pin connected to an analog input on the Arduino (A1), which reads the variable voltage of potentiometer. The motor is connected in series with a current-limiting resistor; one side of the resistor connects to the digital output pin (~5) of the Arduino, and the other side is connected to the anode of the vibration motor. The cathode of motor is connected to the ground. As the potentiometer's resistance changes, the Arduino reads these changes and adjusts the vibration frequency accordingly by varying the PWM signal on pin D5. This setup enables manual control of the frequency of motor through the potentiometer. The following is the circuit diagram of the whole setup of tactile stimulation.

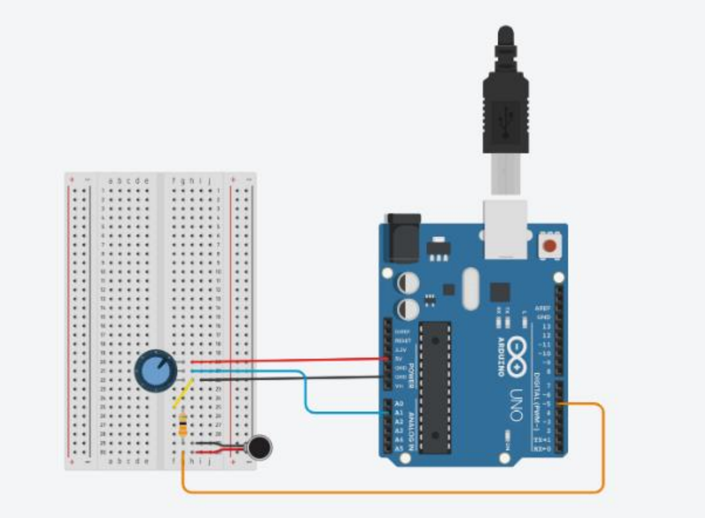


Figure 18: Circuit Diagram

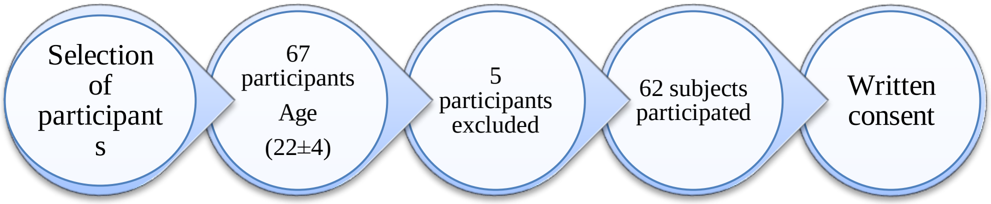
3.4 Experimental Requirements

It is a single session and within-subjects design study. It is employed to investigate the effect of tactile stimulation on visual memory performance of the subject, whether it improves the memory performance or not. An experimental session of tactile stimulations was planned to check effects on memory in Prosthetics and implantology Lab SMME, NUST.

3.4.1 Participants

All the participants were university students. Some participants were undergraduate students, and some were graduate students. Out of 67 participants who underwent the screening procedure, 62 were selected and completed the study (37 females, 25 males; age: 22 ± 4 years). Five participants were excluded from the study.

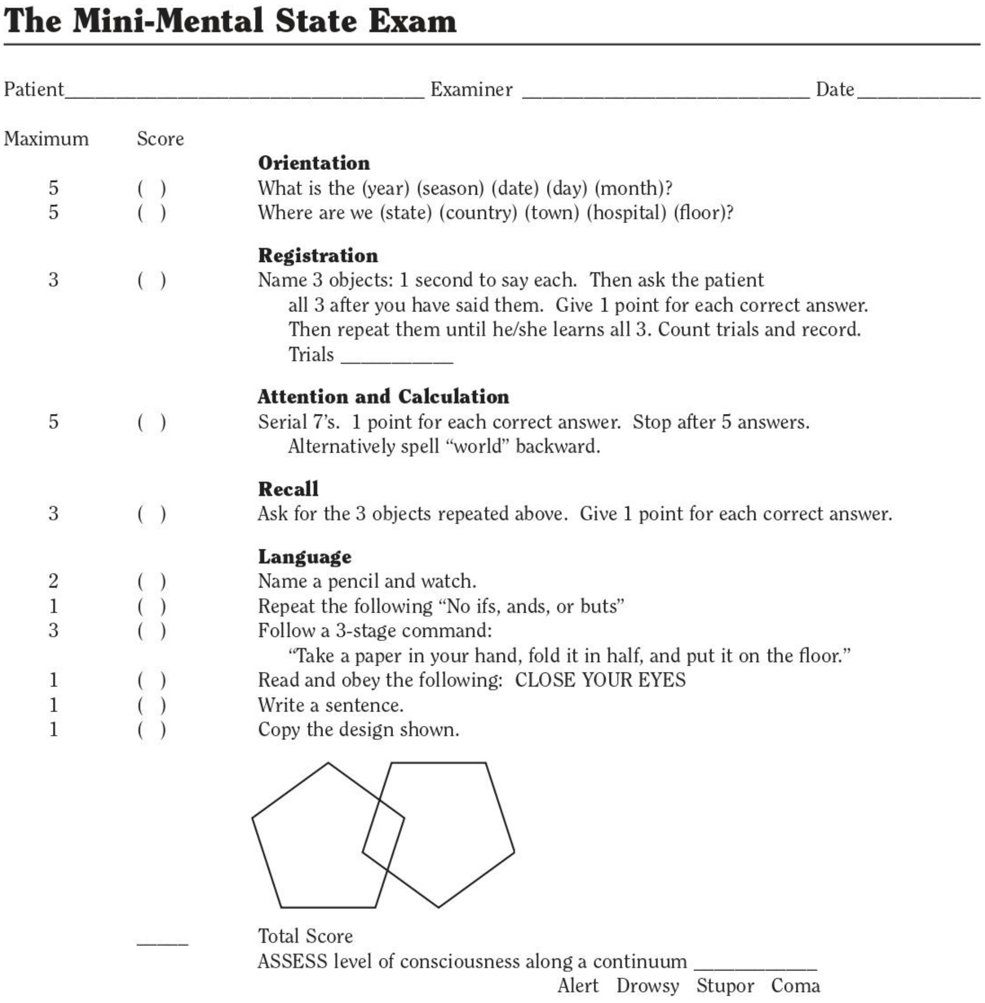
3.4.2 Recruitment



3.4.3 Mini Mental State Examination

It is no longer accepted that cognitive deterioration is a natural and unavoidable aspect of aging. Despite being more vulnerable than the general population, variations in cognitive function frequently necessitate swift and forceful treatment. During illness or injury, cognitive functioning is particularly prone to deteriorate in older adults. Assessing an older adult's cognitive condition by nurses is crucial for spotting early changes in their physiological state, learning capacity, and treatment response.

One instrument for doing a comprehensive and methodical evaluation of mental health is the Mini Mental State Examination (MMSE). Five domains of cognitive function are assessed by this 11-question test: language, orientation, registration, focused attention, calculation, and recall. 30 is the highest possible score. Cognitive impairment is indicated by a score of 23 or below. Because the MMSE only takes five to ten minutes to administer, it is convenient to utilize on a regular basis.



The Mini-Mental State Exam

Patient______________________ Examiner ____________________ Date________

Maximum	Score	
		Orientation
5	( )	What is the (year) (season) (date) (day) (month)?
5	( )	Where are we (state) (country) (town) (hospital) (floor)?
		Registration
3	( )	Name 3 objects: 1 second to say each. Then ask the patient all 3 after you have said them. Give 1 point for each correct answer. Then repeat them until he/she learns all 3. Count trials and record. Trials ___________
		Attention and Calculation
5	( )	Serial 7's. 1 point for each correct answer. Stop after 5 answers. Alternatively spell "world" backward.
		Recall
3	( )	Ask for the 3 objects repeated above. Give 1 point for each correct answer.
		Language
2	( )	Name a pencil and watch.
1	( )	Repeat the following "No ifs, ands, or buts"
3	( )	Follow a 3-stage command: "Take a paper in your hand, fold it in half, and put it on the floor."
1	( )	Read and obey the following: CLOSE YOUR EYES
1	( )	Write a sentence.
1	( )	Copy the design shown.
	_____	Total Score
		ASSESS level of consciousness along a continuum ____________ Alert Drowsy Stupor Coma

Figure 19: Mini Mental State Examination

The MMSE is a useful screening measure for cognitive impairment in older persons who live in the community, are hospitalized, or are institutionalized. Regular, methodical, and comprehensive evaluation of an older adult's cognitive performance yields the best results.

3.4.4 Edinburgh Handedness Inventory

The Edinburgh Handedness Inventory is a tool for measurement used to evaluate laterality, or the dominance of one's right or left hand in daily tasks. The inventory can be utilized by the individual self-reporting hand use or by an observer evaluating the individual. Because a person over assigns duties to their dominant hand, the latter approach is typically less dependable.

3.4.5 Inclusion criteria

All participants underwent screening for neurological, psychiatric as well as for substance misuse or dependence and CNS medication usage. Prior to enrollment, each subject provided their informed consent in the research. First, each subject went through MMSE in order to examine the cognitive ability of the person. The Edinburgh Handedness Inventory was conducted to check the dominant and non-dominant hand of participants [41] [42]. All the subject should have normal vision or corrected to normal vision [43] [44]. None of the subjects should have any type of touch perception impairment and any tactile dysfunction [22].

3.4.6 Exclusion criteria

The following were exclusion criteria: any psychiatric disease, recent history of cerebral infarction, head injury, or seizure, current history of medications or dependence within the last three months, and concurrent medication that was anticipated to impair mental performance. According to the present study, subjects who were using medication currently (within three months), which may have a bad impact on our findings. Participants with any kind of cognitive and touch impairment were also excluded.

3.4.7 Ethical Approval

All the techniques used in this study was approved by the Institutional Ethical Committee, National University of Sciences and Technology (NUST), Islamabad, Pakistan. Prior to the beginning of the experiment, a written signed informed consent was obtained from each enrolled subject.

3.6 Experimental Protocol

The experimental procedure used in this study is depicted in Fig 1. After screening through Mini Mental State Examination (MMSE), each participant attended one data acquisition session lasting for 30 minutes. The visual stimulation in the form of object-number pair assessment task was presented on the laptop screen 90 cm away from the participant. The tactile stimulation in the form of low and high frequency vibration was presented on the index finger dominant hand of the participant.

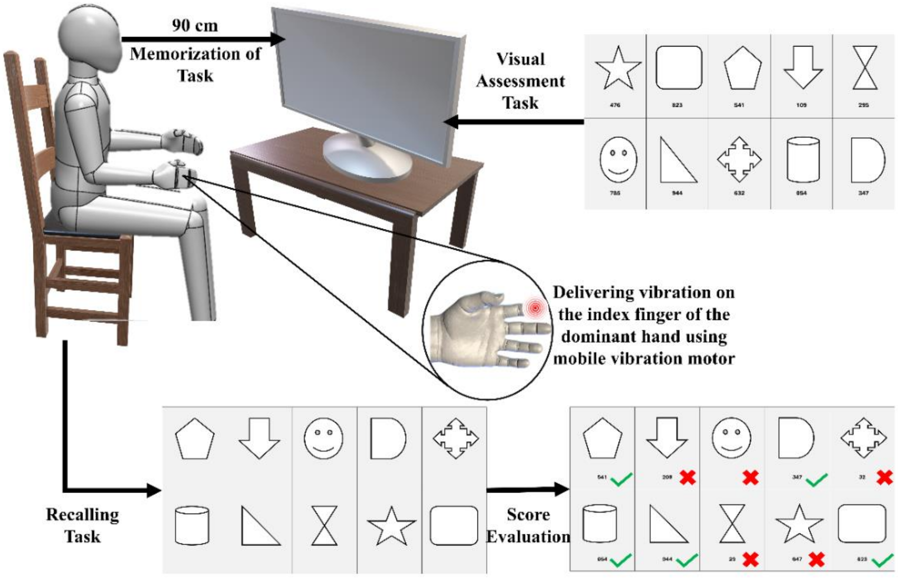


Figure 20: Experimental Setup

During the experiment, each participant was instructed to sit in a chair in a relaxed position with their hands resting on the armrests. Two groups, Group a and Group b, were randomly assigned to the participants. There were eleven males and twenty-one female participants in each group, total thirty-one participants in each group. While watching the visual presentation, they received tactile stimulation vibrations on the index finger. To counterbalance the sensitivity of vibrations for participant, the sequence of tactile stimuli was altered. The no stimulation condition is employed as a control condition in contrast to the tactile stimulation setting. Every participant encountered the no stimulation condition before moving on to the active condition/stimulation condition.

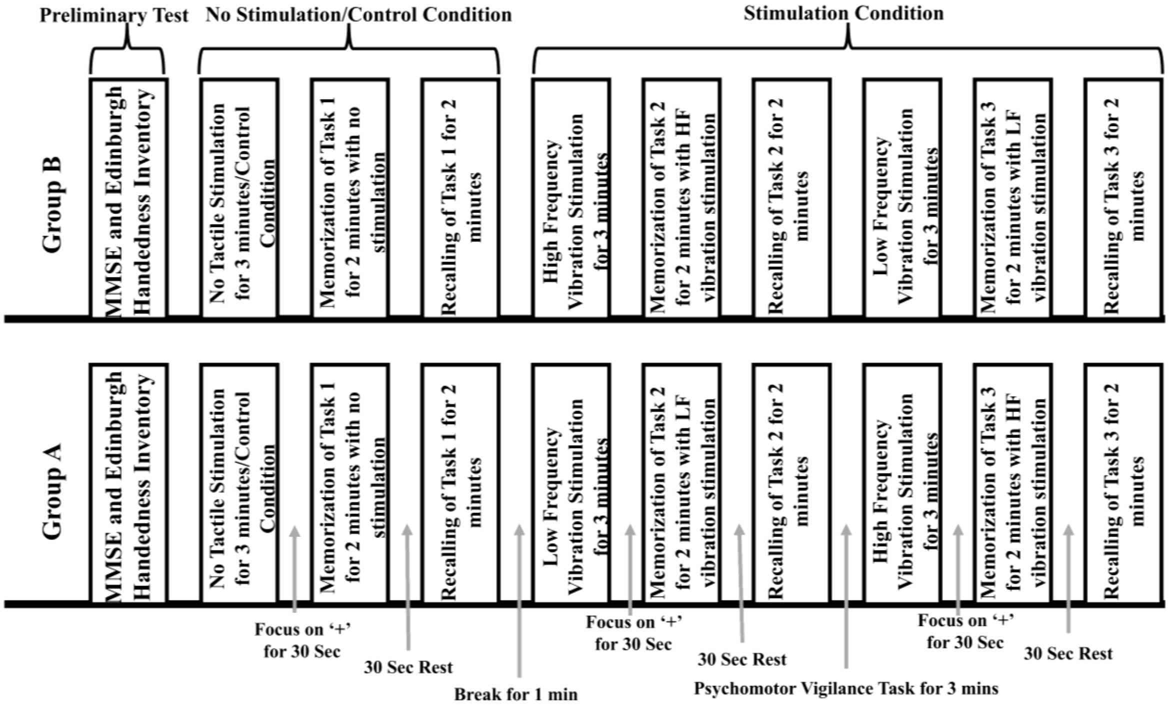
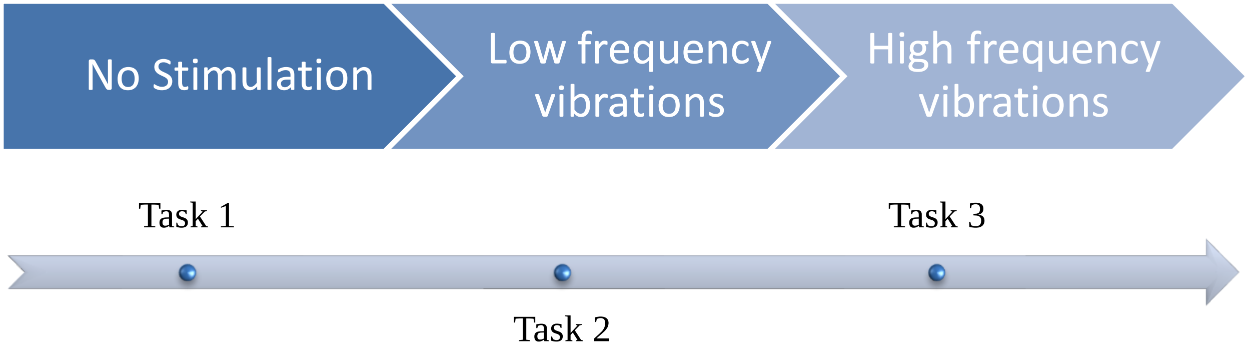


Figure 21: Timeline for Experimental Procedure

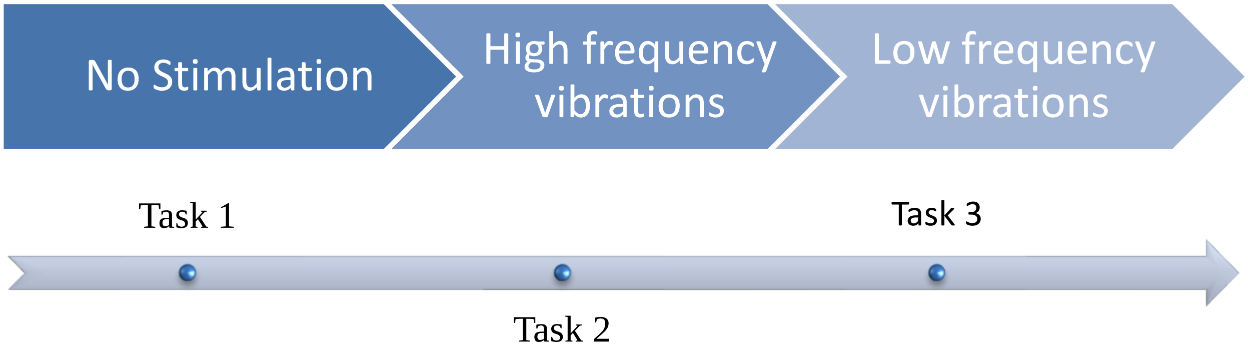
First, MMSE and EHI were conducted which lasted for 15 minutes. After this, a mobile vibration motor tapped around the palmar side of the index fingertip of the dominant hand of the subject for 3 minutes without any stimulation. Then, a video of 5 minutes was played on the screen of the laptop containing visual stimulus. At start the "+" was displayed for 30 seconds so that participant became focused on the screen for the task. After that a visual stimulus in the form of object-number pair task was presented for 2 minutes with the motor attached to the index finger. Before recalling the task given to the participants they were provided with the rest of 30 seconds. During his break period the motor was unwrapped from finger. They were provided with the paper containing shapes only; participants wrote the number corresponding to the shape in 2 minutes. After the break of 1 minute, each subject went through the same procedure as used in control condition except in active condition they were provided with tactile stimulation in the form of low and high frequency vibration. Group 'a' participants memorized first under control condition which is no stimulation state, then they received low frequency vibrations and before high frequency vibration stimulation they performed a psychomotor vigilance task to sustain their attention even during the last task. Group ‘b’ participants followed the same process except in this group the low frequency vibration provided first and then high frequency vibration [44] [45].

All the 62 participants divided in half randomly with order of stimulation as shown in the figure below:

Group a:



Group b:



3.6.1 Visual Stimulation

The participants must retain numbers and shape of objects to memory as part of the visual stimulation. Black, grey, and white color schemes in the visual assessment tasks were used to reduce the impact of color on participant performance. To standardize the time of experimental procedure for each participant, a video is designed using YouCut-Video Editor Software. The '+' sign appears for a brief period of 30 seconds at the beginning of the 5-minute video to encourage participants to keep their focus on the screen. After that, for two minutes, a visual stimulus in the form of 10 distinct shapes with corresponding three-digit numbers was displayed [46]. The participants were given a page with shapes to assist them recall the task for a maximum of two minutes following the 30 second break. The 3 different tasks were presented to each participant at control condition, high frequency and low frequency stimulation conditions. Each of the ten distinct shapes is given a three-digit number to ensure that the difficulty of task is neither excessively high nor low.

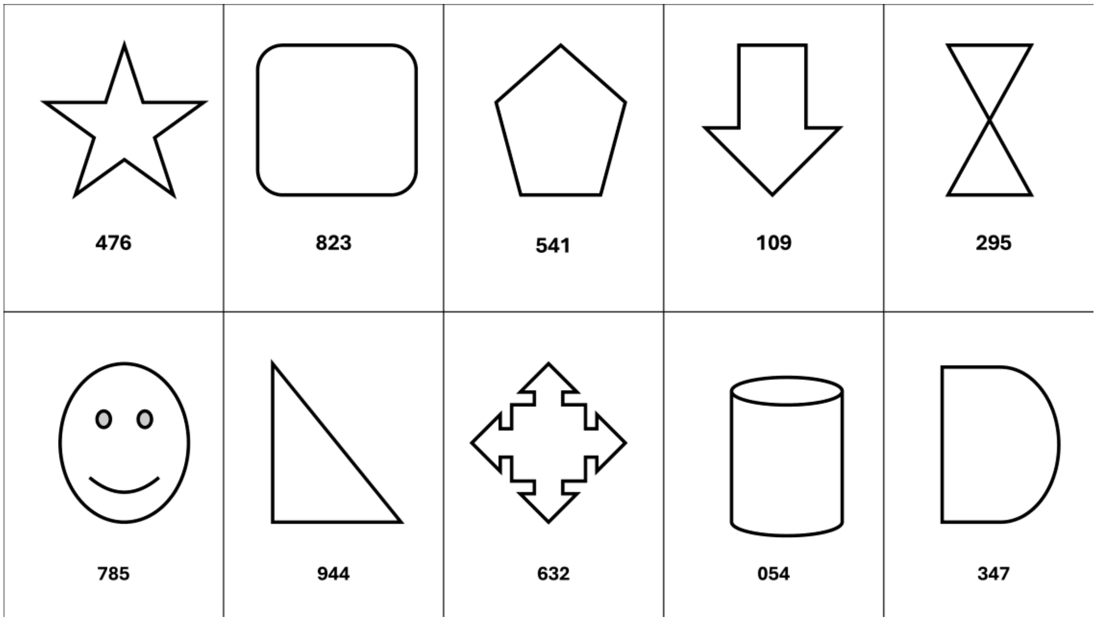


Figure 22: Visual Task 1

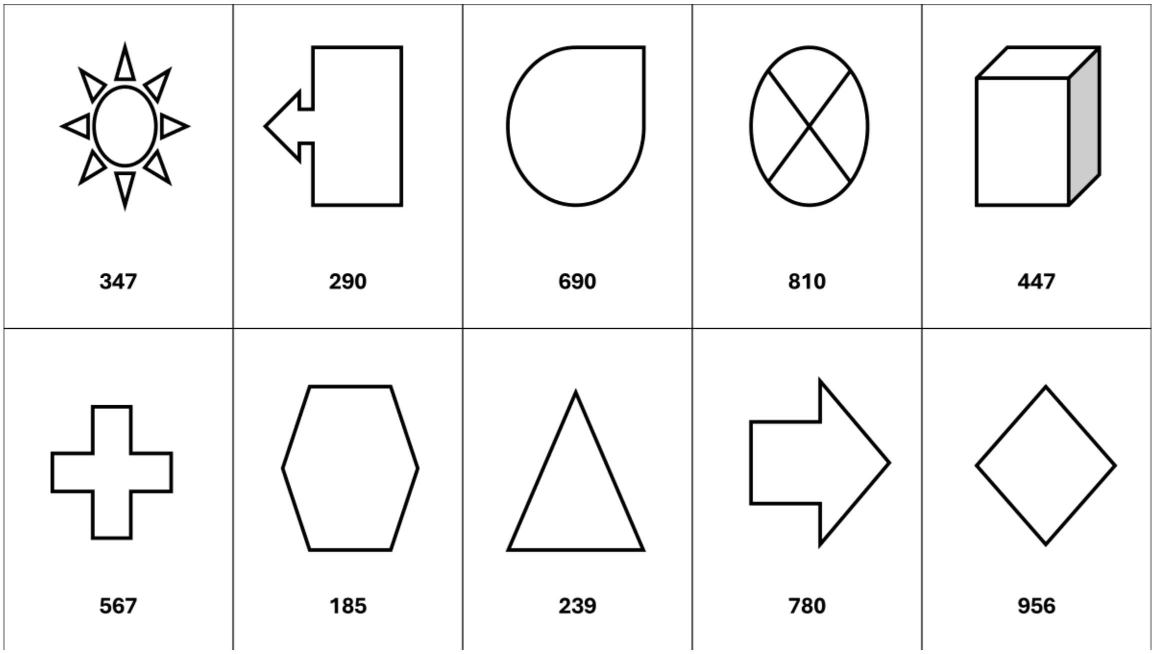


Figure 23: Visual Task 2

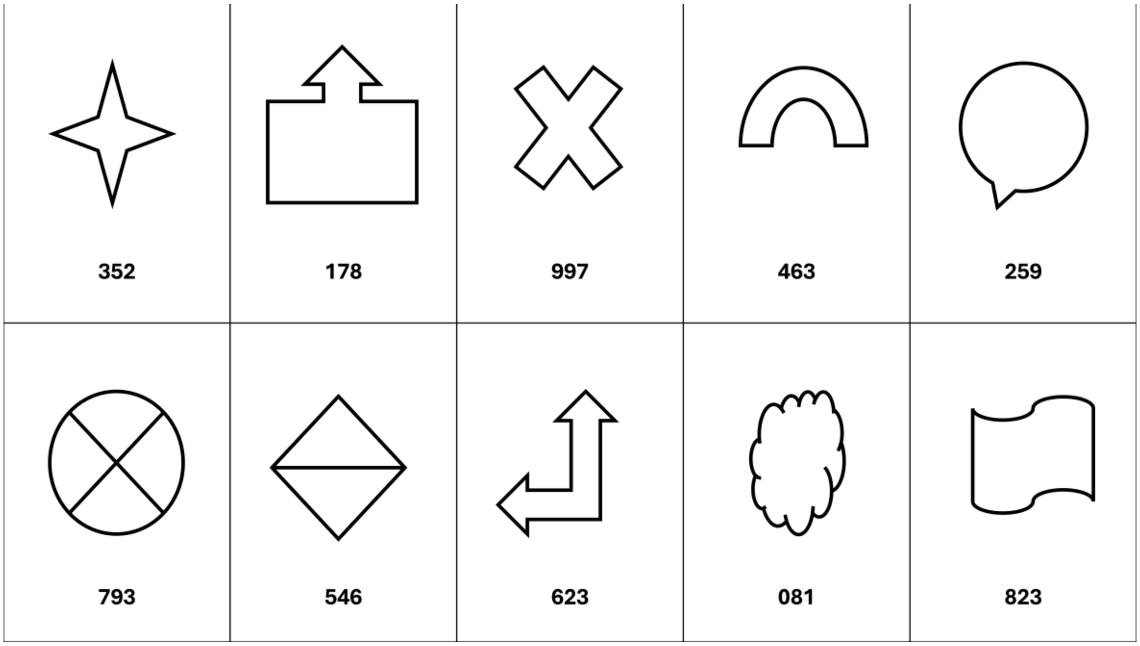


Figure 24: Visual Task 3

3.6.3 Score Evaluation

The visual memory of the subject after tactile stimulation is tested using the score evaluation. It is determined if the participant can accurately recall the information. First, within the given time frame, participants must encode the object and its associated number to memory. After that, the answer sheet was given out, as seen in Fig 3 (A). This evaluation sheet had different arrangement of shape. A more equitable and accurate evaluation of memory recall can be achieved by altering the arrangement of shapes to lessen the influence of biases such as familiarity bias, positional bias, and serial position effect. By using this method, the assessment is guaranteed to assess actual memory recall and connection rather than location familiarity or pattern recognition. The missing number for each object should then be filled in. When the shape of the object and its matching number are coupled correctly, the answer was considered correct. The subject received one score for correctly matching shape and numeric variables. A subject may receive a total valid score of 10 if he/she could recognize all the ten shapes with their corresponding number correctly. Each blank, partially and incorrectly written number assigned zero score. The significance of score variations between conditions was examined using the sign test. The memory performance of the participants was evaluated using this score evaluation. The individual high visual assessment score suggests that they were able to memorize more items to memory. This assessment is essential for evaluating how tactile stimulation affects the visual memory of the participant.

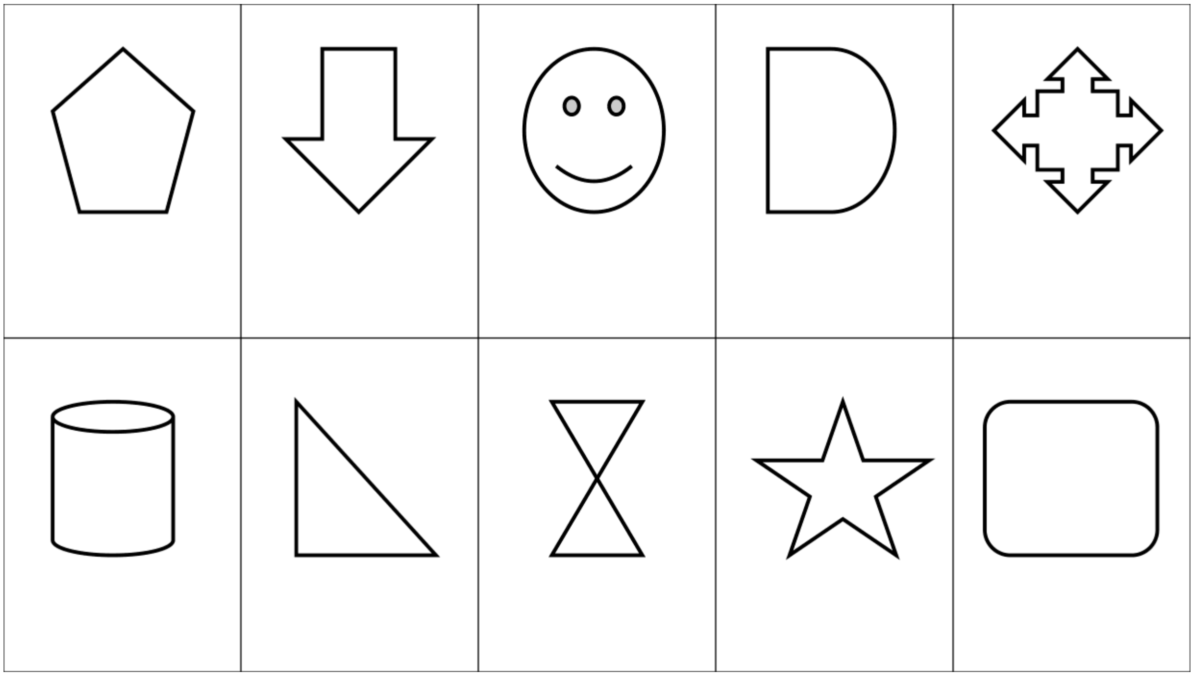


Figure 25: Visual Task 1 Recalling Sheet

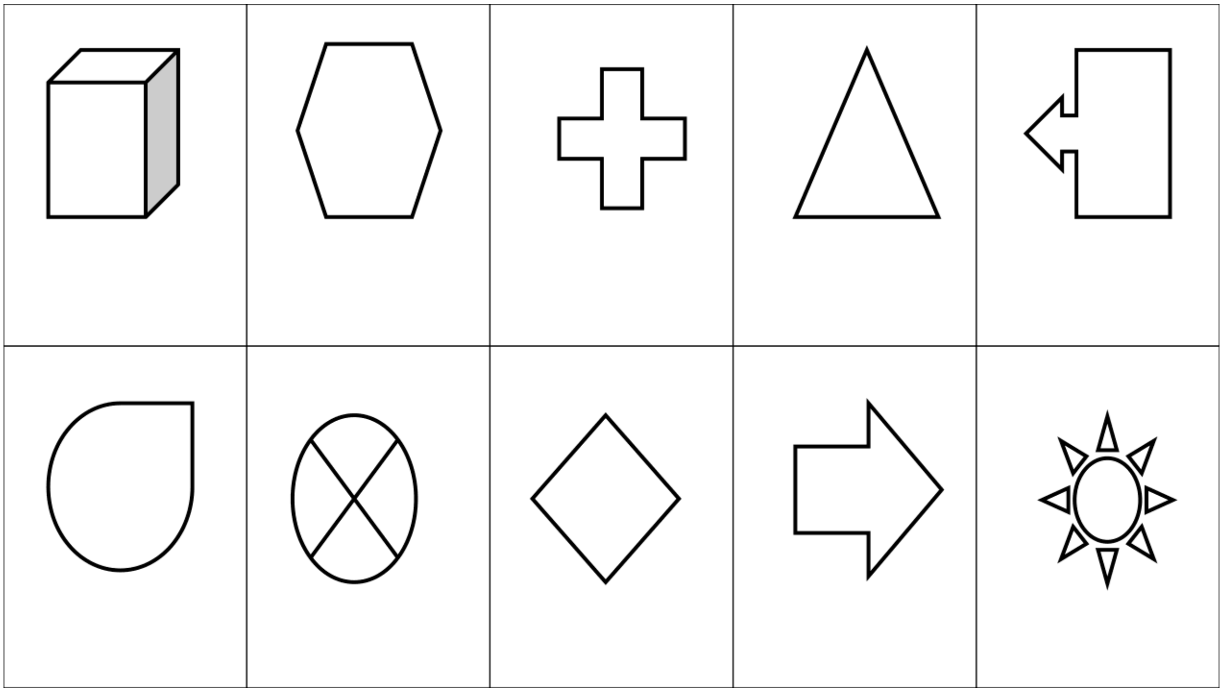


Figure 26: Visual Task 2 Recalling Sheet

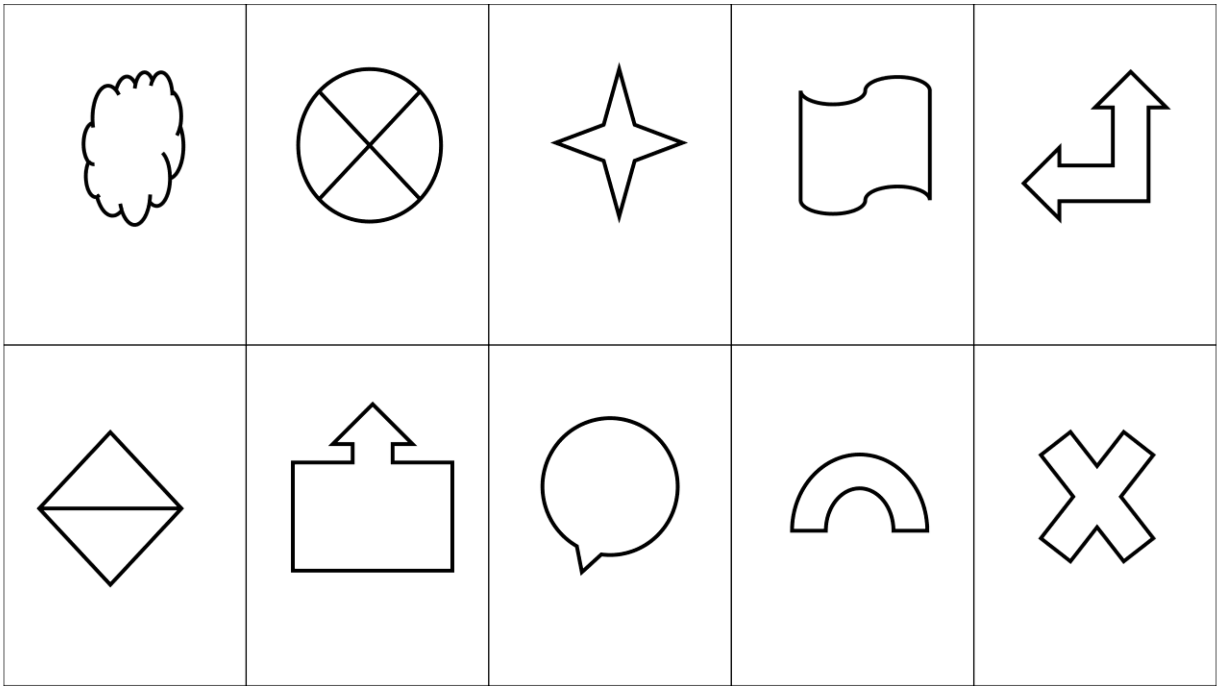


Figure 27: Visual Task 3 Recalling Sheet

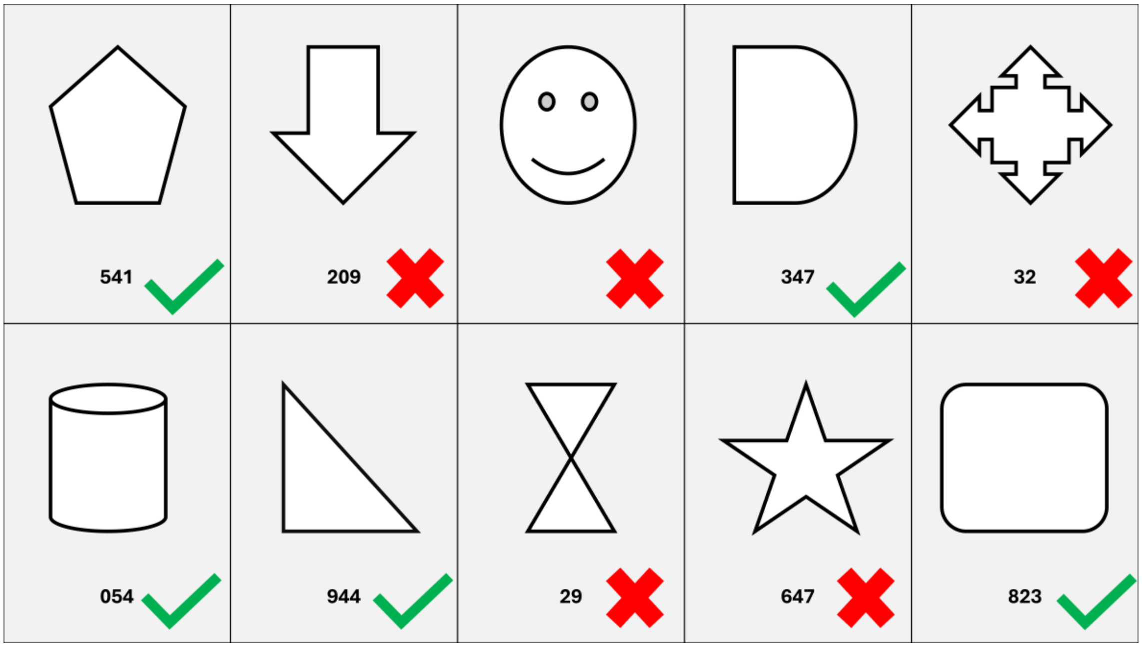


Figure 28: Visual Task 1 Evaluation Sheet

3.6.2 Tactile stimulation

The device delivering vibration was developed as shown in Fig 4 and the parameters were set as described below:

Vibrations delivering device

The vibration delivering device was made up of a mini mobile vibration motor. An eccentric rotary mass is used by this mobile vibration motor to transform electrical power into mechanical vibrations that cause movement. This vibration motor was controlled using Arduino UNO. The driving voltage on which the mini mobile motor works is adjustable between 3.3V to 5V. The vibrations of frequency ranging from 0 to 300 Hz can be produced.

Low and high frequency vibrations

The sensory mechanoreceptors on the human body are of four types. Out of these the two mechanoreceptors i.e. Pacinian and Meissner Corpuscles are the natural vibration detecting device on the body. Human bodies have Meissner and Pacinian mechanoreceptors that are capable of detecting vibrations at frequencies between 20 and 50 Hz and higher than 100 Hz respectively [47] [48]. The vibration of low frequency of 35 Hz activating the Meissner corpuscles and high frequency of 250 Hz triggering the Pacinian corpuscles was delivered on the index finger of the dominant hand of each participant. The vibration was delivered during the active /stimulation condition to each participant of group A and B for 5.5 minutes. For 3 minutes the vibration stimulation was provided without visual stimulus. Then after this, for 30 seconds "+" sign was displayed on the screen and for 2 minutes the visual assessment task was presented along with tactile stimulation in the form of vibration. At the time of retrieval of task tactile stimulation was not provided.

CHAPTER 4: IMPLEMENTATION AND RESULTS

In this study, we made a customized tactile stimulation device that was used during delivery of low and high frequency vibration for all the participants. A mini mobile flat shaped motor was controlled by the Arduino UNO, and it helped in the smooth conduct of whole experimentation for data collection. The real time picture of this device is as shown in the figure below.

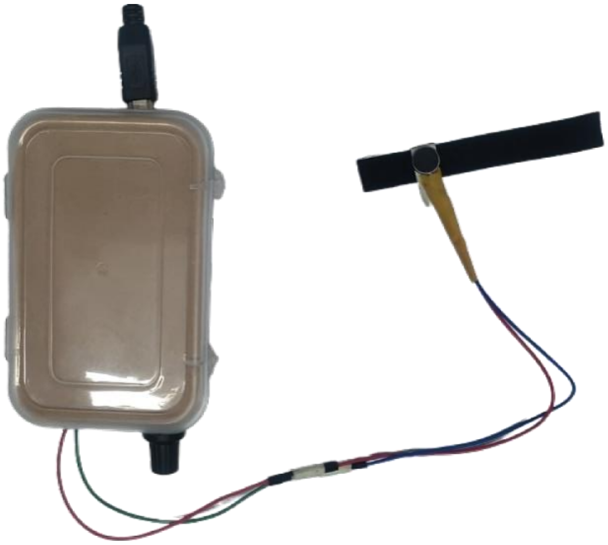


Figure 29: Tactile Stimulation Device

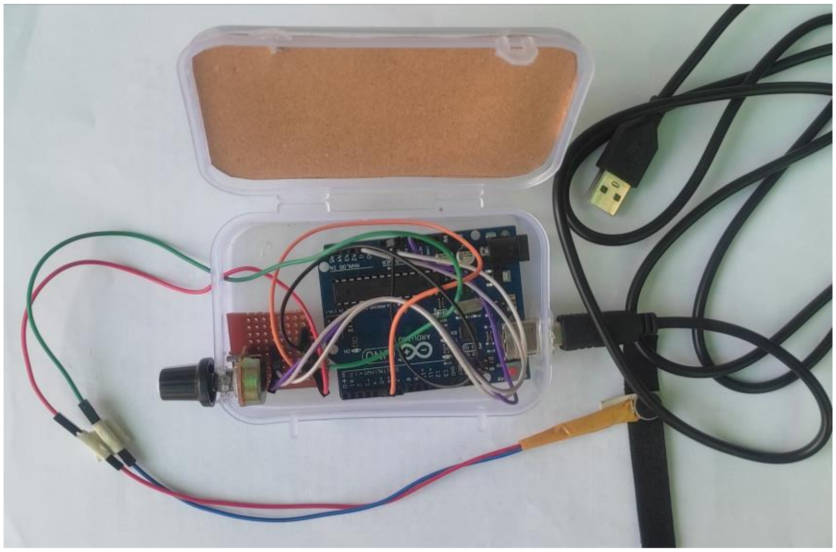


Figure 30: Designed Circuit for Tactile Stimulation Device

Repeated measures ANOVA was conducted on the performance scores of Groups a and b under different conditions (no stimulation, low-frequency vibration, and high-frequency vibration) to test the hypothesis that is effect of tactile stimulation on enhancing visual memory performance. This statistical analysis was designed to directly compare within-subject factors (performance scores under no stimulation, low vibration, and high vibration conditions) and between-subject factors (Group a and Group b) to determine if there are any significant differences in visual memory performance due to the sequence of tactile stimulation.

4.1 Normality Test

To ensure that the assumptions of the repeated measures ANOVA are met, a Shapiro-Wilk test was conducted to check the normality of all factors: comparing the visual memory performance scores of both Group A and Group B under each stimulation condition (no stimulation, low-frequency vibration, and high-frequency vibration). The findings suggest that the p-values for all conditions are greater than 0.05, indicating that each of the factors is normally distributed within the population. This means that the visual memory performance scores under all stimulation conditions (no stimulation, low vibration, and high vibration) for both groups are normally distributed, as required for the application of repeated measures ANOVA. The normality test results for visual memory scores under each stimulation condition for both Group A and Group B are as follows.

Stimulation Condition	Valid N	Mean	Minimum	Maximum	Standard Deviation
No stimulation	62	4.69	0	9	2.12
Low Vibration	62	5.35	1	10	2.00
High Vibration	62	5.50	2	10	1.94

Table 3: Descriptive Statistics

The mean and standard deviation test scores along with maximum and minimum values at all three conditions i.e. No stimulation, Low frequency and high frequency is represented in the table 1.1. At control condition which is no stimulation, mean value and standard deviation of assessment test is 4.693 ±2.116. At low frequency condition, 5.354 ±2.000 is mean and standard deviation of the test score. At high frequency condition, the mean and standard deviation is 5.500 ±1.939.

4.2 Effect of Stimulation on Visual Memory

Further, the statistical analysis is also applied on all three stimulation stages i.e., no stimulation, Low frequency vibration stimulation and high frequency vibration stimulation stage. Figure 1.2 shows that there exists a statistically significant difference in the means of memory score at each of three stimulation stages. The current effect of condition on memory score is F (2, 122) = 6.2099 and the p value is 0.00270 as shown in figure 1.2.

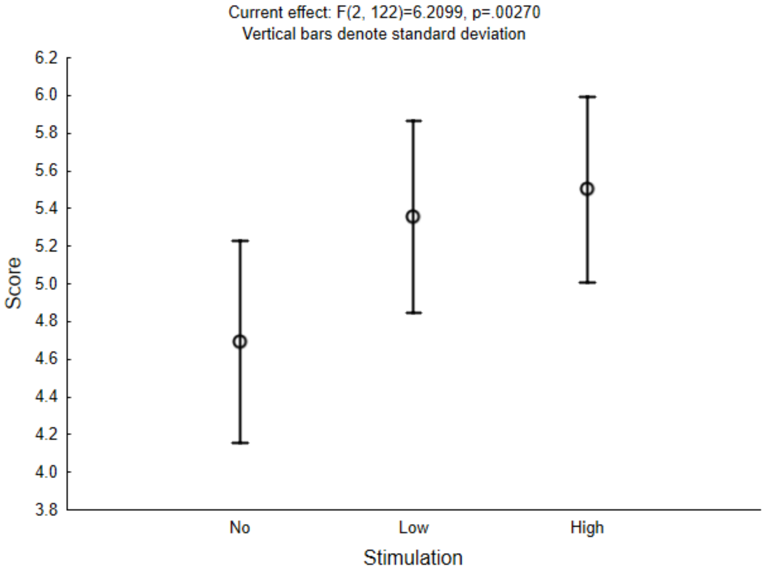


Figure 31: ANOVA results showing the effect of tactile stimulation on memory

As the p value is far smaller than 0.05 it evident that stimulation has a significant effect on the memory performance score. In other words, we reject the null hypothesis and conclude that there is significant difference in the means of memory score at different stimulation conditions. Despite that there exists overlapping in the confidence intervals at control, low and high stimulation stages, the statistical analysis suggests that overall difference among the stimulation stages is still significant.

4.2.1 Results from analysis of repeated measured ANOVA

To examine how memory performance of the participants differs at different stimulation stages i.e. at no stimulation, at low frequency stimulation and high frequency stimulation. Table 1.3 show values obtained from repeated measure ANOVA. The p=0.002702 shows that there is a significant difference in memory performance at three different stages of stimulation.

Effect	**SS**	**Degree of Freedom**	**MS**	**F**	**P**
Intercept	4996.215	1	4996.215	584.0895	0.000000
Error	521.785	61	8.554		
FREQ	22.914	2	11.457	6.2099	0.002702
Error	225.086	122	1.845		

Table 4: Results of Repeated Measure ANOVA

4.2.2 Post hoc analysis

To identify that at which stimulation stage the memory performance of participants is significant we implement post hoc analysis. Table 1.4 show the Tukey's test analysis. From table 1.3 we observe that there is significant difference between the memory scores at control and low frequency stimulation as the p=0.018438. The p=0.002733 value shows an even more significant difference between control and high frequency stimulation. But there is no significant difference between low frequency stimulation and high frequency stimulation stage.

Group	**Control**	**Low**	**High**
	4.6935	**5.3548**	**5.5000**
Control	-	0.018438	0.002733
Low	0.018438	-	0.822791
High	0.002733	0.822791	-

Table 5: Post hoc Analysis

4.3 Effect of Sequence of Stimulation on Visual Memory Performance

As all the 62 participants were divided into two groups i.e. Group a and Group b. The 31 participants of the group A followed the following sequence of stimulation: no stimulation, low frequency vibration stimulation and high frequency vibration stimulation. While all 31 other participants of group b followed the following sequence: no stimulation, high frequency vibration stimulation and low frequency vibration stimulation.

The overall memory score shows that there is no significant effect of stimulation sequence of tactile on visual memory performance Group a and Group b. Graph shows the current effect of order of stimulation on memory score is F (1, 60) = 0.81206 and the p value is 0.37111 with the confidence interval of 95%. This is further supported by the fact that the confidence intervals overlap, since non-overlapping confidence intervals usually indicate significant difference visually.

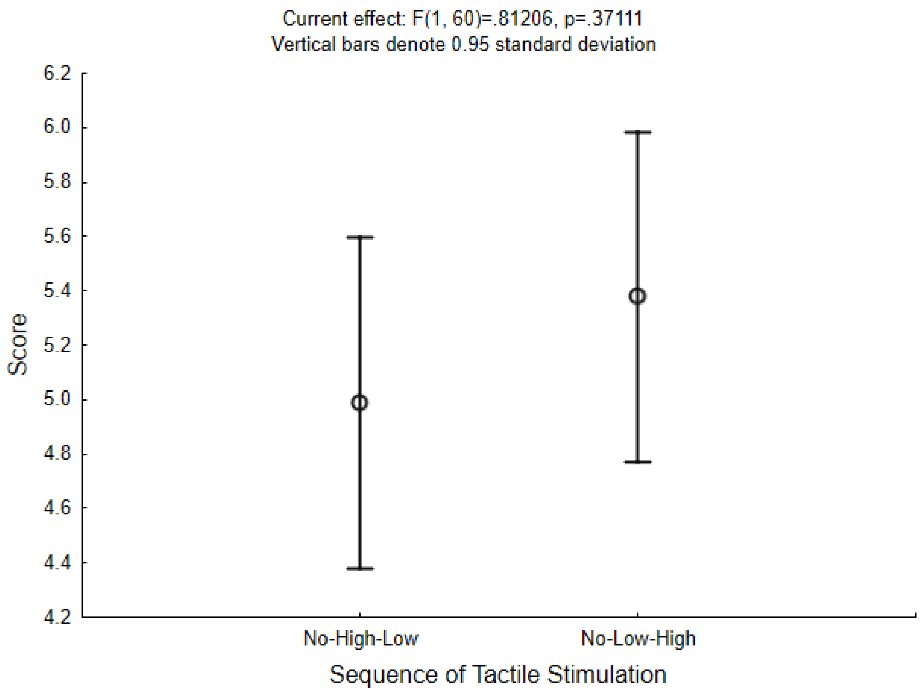


Figure 32: Effect of sequence of vibrotactile stimulation

Group	F	df(numerator)	df(denominator)	p-value	Significance
Group a & Group b	1.4049	1	60	>0.05	Highly non-significant

Table 6: Effect Sequence of Vibrotactile Stimulation

4.4 Effect of Frequency and frequency*group on visual memory performance

The main effect of the frequency is determined by using multivariate test for repeated measure as shown in table 1.2 below. The large Value of F= 5.015222 indicates more evidence against null hypothesis in case of FREQ. The statistically significant p value of 0.009737 shows that there is significant influence of frequency on memory. While the interaction between frequency and condition is determined by F value of 0.135261 shows that it strongly supports the null hypothesis. The p value of 0.873758 for the FREQ*group shows that there is no significant effect of interaction of frequency and condition on the memory scores. This is a positive aspect of this study that it does not matter whatever the sequence of the vibrations (low and high frequency) delivering to the participant.

Effect	**Test**	**Value**	**F**	**Effect df**	**Error df**	**P**
FREQ	Wilks	0.854695	5.015222	2	59	0.009737
FREQ * group	Wilks	0.995436	0.135261	2	59	0.873758

Table 7: Significance of Tactile Stimulation and Groups

4.5 Effect of visual assessment task type on visual memory performance

As we discussed earlier, the sequence of tactile stimulation did not affect the visual memory performance in both groups. However, at three different stages of stimulation i.e. No stimulation, Low frequency vibrations and High frequency vibration, we provided the participants with three different task types i.e. Task 1, Task 2 and Task 3 respectively. In order to investigate how the task type affects visual memory at different stimulation conditions. All the participants performed Task 1 at no stimulation conditions. Task 2 was performed by participants at low and high frequency stimulation condition. Also, Taks 3 performed by participants at low and high frequency stimulation condition.

4.5.1 Effect of type of task on visual memory at low frequency vibrations

The p>0.05 suggests that there is no significant effect of task type on visual memory scores at low frequency vibration stimulation.

Effect	SS	Degrees of Freedom	MS	F	P
Intercept	1781.042	1	1781.042	443.9656	0.000000
Task Type	3.494	1	3.494	0.8708	0.354461
Error	240.700	60	4.012		

Table 8: Effect Type of Task at Low Frequency Vibration

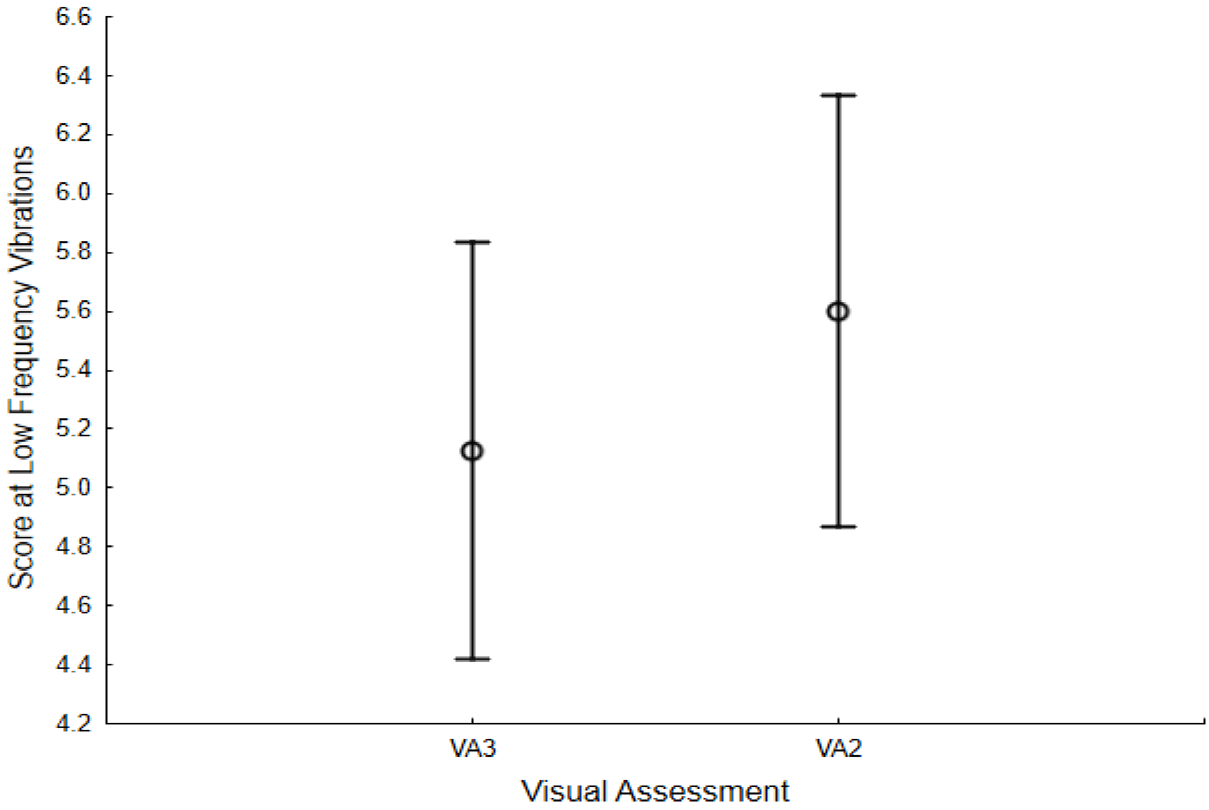


Figure 33: Effect of visual assessment on memory at low frequency vibrations

4.5.2 Effect of type of task on visual memory at high frequency vibrations

The p=0.436344 suggests that there is no significant effect of type on visual memory scores at high frequency vibration stimulation.

Effect	SS	Degrees of Freedom	MS	F	P
Intercept	1877.809	1	1877.809	495.9548	0.000000
Task Type	2.325	1	2.325	0.6141	0.436344
Error	227.175	60	3.786		

Table 9: Effect Type of Task at High Frequency Vibration

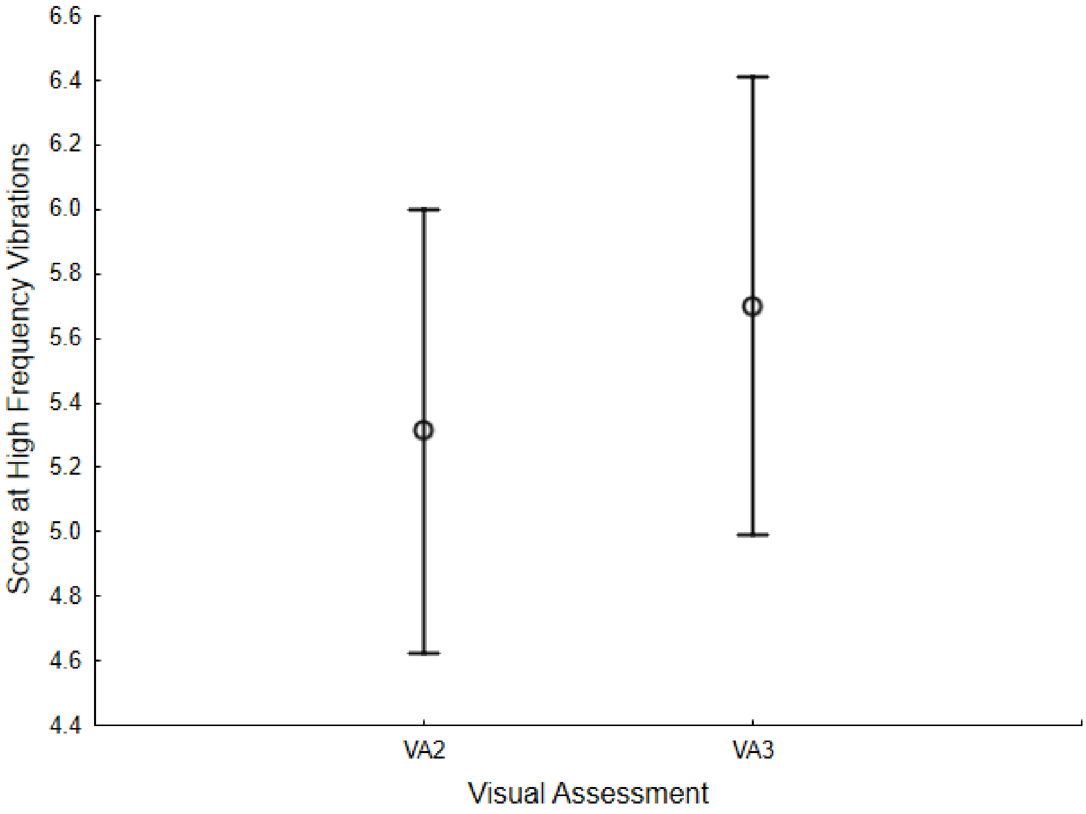


Figure 34: Effect of visual assessment on memory at high frequency vibrations

CHAPTER 5: DISCUSSION

Tactile stimulation in the form of low and high frequency vibrations corresponding to natural responding vibrations for Meissner and Pacinian corpuscles is purpose to a non-invasive and non-pharmacological way to improve visual memory performance. Some previous suggested that auditory circumstances like White Noise and Mozart Music is effective for improving visual memory performance using EEG analysis [45]. In fact, very little study has been done on how tactile stimulus, especially vibration, affects visual memory function.

The results of this study indicate that visual memory capacity is significantly impacted by tactile stimulation in the form of vibrations, which correspond to the low-frequency and high-frequency natural response frequencies of Meissner's corpuscles and Pacinian corpuscles, respectively. This observation provides significant new information on an association between memory cognition and sensory systems.

The results of ANOVA showed that there is a significant difference between memory scores at no stimulation, low frequency vibrations and high frequency vibrations. Tactile stimulation aimed at the Pacinian and Meissner corpuscles improves visual memory function, indicating a novel approach for sensory modulation of memory. Although haptic memory has long been associated with tactile stimulus, its cross-modal effects on visual memory are less well recognized. This research shows that frequency-specific tactile stimulation may serve as an additional cue in memory storage and retrieval, which may not have been commonly identified.

This study offers an important contribution to the larger field of multimodal processing by showing how tactile stimulation can affect cognitive processes like memory when it is precisely designed to connect with mechanoreceptors. The functions of Pacinian corpuscles, which are sensitive to high-frequency vibrations, and Meissner's corpuscles, which are in sensitive to low-frequency vibrations, in both the temporal and spatial resolution of touch are well recognized. Perhaps because of common neuronal pathways in the visual and somatosensory cortices, their stimulation seems to improve cross-modal integration.

The findings support the important hypothesis that tactile stimulation can interfere with visual memory function. They offer proof that frequency-specific tactile stimulation improves the capacity of the brain to encode and retrieve visual information by aligning the natural features of mechanoreceptors. This supports the notion that improving neuronal plasticity and cognitive performance through sensory integration across modalities. According to the co-activation hypothesis discussed in this paper [49], multisensory integration may improve cognitive responses by strengthening signals processed in certain brain regions.

Vibrotactile stimulation through transcutaneous auricular vagus nerve was found [50] to significantly improve working memory performance during 4-back tasks. This suggests that stimulation can increase cognitive resources and attention, which is consistent with the notion that tactile stimuli can improve task outcomes and prioritize attention. In the same way our study approves that vibrotactile stimulation on right index fingertip could enhance visual memory.

The post analysis results show the most significant stimulation condition is high frequency vibration stimulation which influences most visual memory. There is no significant difference in the test score between low and high frequency vibration stimulation. There also exists a significant difference between no stimulation condition and high frequency vibration stimulation but it is less than a significant difference at no stimulation and high frequency vibration stimulation. This hypothesized that for improvement in visual memory, high frequency vibration is the most effective method.

In the previous studies, it is suggested that the sequence of auditory circumstance does not affect the visual memory performance [44]. We also divided the participants into group a' and group 'b', provided randomized tactile stimulation sequence. The $p > 0.05$ suggests that there is no significant effect of sequence tactile stimulation on visual memory performance. It provides the important aspect of this study that improvement in memory performance is independent of sequence of tactile stimulation. However, other demographic factors may affect visual memory but are not influenced by the sequence of tactile stimulation.

One of the most significant outcomes from this study is that visual memory performance does not depend on the type of task. In this study, we provide the participants with three different tasks at three different stimulation stages i.e. No stimulation, Low frequency vibration and High frequency vibration. Participants performed Task 2 and Task 3 at low frequency stimulation. Likewise, with high frequency vibration stimulation we provided participants with Task 2 and Task 3. But at no stimulation condition all the participants performed Task 1 only. We compared the performance of subjects during low frequency stimulation with Task 2 and Task 3, result suggested that there is no significant effect of different type of task at low frequency stimulation. We also compared the performance of subjects during high frequency stimulation with Task 2 and Task 3, result showed that there is no significant effect of different task types at low frequency stimulation. The statistical results show that there is no significant impact of type of task on visual memory at different stimulation conditions. The improvements in the visual memory is independent of the type of visual assessment task.

For the best learning and memory performance, it has long been believed that a quiet, distraction-free environment is essential. Cognitive psychology supports this idea, arguing that auditory, visual, or tactile distractions may overload the working memory and impair the effectiveness of storage and retrieval processes. Distractions or noise make the brain shift its focus between the learning activity and the distraction, which makes it harder to concentrate and increases cognitive load. Long-term memory encoding requires continuous attention, which is facilitated by a calm setting. Multitasking can decrease learning efficiency since the brain finds it difficult to distribute resources efficiently.

Interestingly, this research shows that even in situations where traditional learning theories forecast distractions, tactile stimulation in the form of vibration improves memory recall and scores. According to this research, some forms of stimulation may be helpful for learning rather than harmful.

According to earlier studies on cross-modal attentional interactions, sensory modalities such as the tactile, visual, and auditory systems, interact to improve cognitive functions like perception and attention rather than operating separately. For instance, research by Caclin, A., et al. [51] and Spence, C. [52] demonstrated how tactile stimuli can enhance perceptual accuracy in multimodal tasks and focus visual attention. These researches showed that tactile cues aid in directing visual focus in complicated sensory contexts, with a primary focus on immediate attentional effects. Our study, on the other hand, adds to this knowledge by demonstrating that tactile stimulation more especially, vibrations that target the Meissner's and Pacinian corpuscles, not only affect attention but also significantly affects visual memory function. Investigating how tactile inputs improve long-term cognitive functions like memory storage and recall has replaced the focus on short-term attentional mechanisms. Our study makes a unique contribution to the field by proving that cross-modal interactions can facilitate memory, whereas earlier studies focused on perceptual outcomes.

A study by Dehghan Nayyeri, M., et al. [22] revealed that performance on a verbal n-back test was not significantly impacted by tactile pressure applied, suggesting that low salient tactile stimuli may not have an impact on working memory tasks. According to the analysis of the fMRI data, the n-back task and tactile salient pressure did not significantly interact. This implies that the brain activity linked to the working memory tasks was unaffected by the tactile pressure, suggesting that the tactile input was not conspicuous enough to have an impact on cognitive processing. This present study overcomes the limitation of this study that a fast adaptation of mechanoreceptors to this stimulus is the risk of using constant salient tactile pressure. The tactile stimulation in the form of continuously varying frequency vibration might reduce the fast adaptation of Meissner and Pacinian corpuscle mechanoreceptors. This means that the activation of mechanoreceptors results in improvement in visual memory performance. This interaction of tactile stimulation in the form of vibration with visual task may facilitate a useful cognitive function like memory.

The vibrotactile stimulation is results in the activation of secondary somatosensory cortex reported by previous studies [53] [54]. Frequency-specific high-gamma activity in the primary (S1) and secondary (S2) somatosensory cortices are key to the neural mechanisms underlying vibrotactile perception. S1 processes early responses, whereas S2 displays later, frequency-dependent activations that are essential for complex high frequency vibrotactile perception [33]. The parietal cortex including the somatosensory cortex is responsible for the higher level of tactile stimulation processing [55]. The visual working memory task performance results in the activation of fronto-parietal network is investigated by various studies using fMRI analysis. The study finding positive impact of vibrotactile stimulation on visual memory performance hypothesized that common area of parietal network responsible for activation during tactile stimulation processing and visual working memory task may facilitate improvement in high cognitive functions like visual memory.

Our results support the findings of prior study [56] by showing that cross-modal activation of neural networks, specifically the visual network (VIN) and sensorimotor network (SMN), through vibrotactile stimulation on the fingertips improves visual memory performance. The research emphasizes how somatosensory areas, such as the inferior parietal lobule, postcentral gyrus, and precentral gyrus, facilitate cross-modal interactions and allow tactile information to affect memory and visual processing. It also highlights the significance of frequency-specific stimulation, since specific frequencies (30 Hz to 240 Hz) are the most effective at activating sensory mechanoreceptor receptors and improving neural connectivity. Together, the results indicate that tactile stimulation improves memory and attention by enhancing functional connection between sensory and cognition networks.

The observation that tactile stimulation, especially vibration, improves visual memory function has major implications for a number of diverse fields. By showcasing the brain's extraordinary capacity to integrate sensory inputs to enhance cognitive processes, it contributes to our knowledge of multisensory integration. Cross-modal plasticity theories, which postulate that stimulating one sense can have a favorable impact on another, are supported by this. These findings may open the door to non-invasive methods of improving cognitive function, providing fresh approaches for people suffering from neurological conditions like cognitive impairment. Additionally, the results can be used to create instructional resources and multimodal learning settings where tactile input can help with memory retention. The capacity of sensory input in the form of tactile stimulation to enhance user interaction and cognitive function in a variety of contexts is further highlighted by their potential for advancements in virtual reality, rehabilitation, and human-computer interface.

5.1 Limitations

This study has important limitations that should be carefully taken into account when evaluating the findings. The primary limitation of this study is it only focused on visual memory performance of adults. It limits to evaluate the effectiveness of tactile stimulation on other people. As the sample was homogenous so the improvement in visual memory due to tactile stimulation remained unclear for heterogenous sample.

Secondly, in the study there was not any type of neural investigation done which resulted in limiting understanding of neural network and mechanisms. This method offers little information about the ways in which tactile stimulation affects the brain networks that encode, store, or retrieve visual memories. Furthermore, behavioral measures are vulnerable to outside factors that could introduce variability or confounding in the data. Determining whether reported effects are caused by modifications in sensory integration, focus, or memory pathways is similarly difficult in the absence of additional tests like EEG or fMRI. As a result, behavioral study might provide a basic understanding of how tactile stimulus affects visual memory without exploring deeply into the underlying mechanisms.

Lastly, all the participants were right-handed. To strengthen and validate the efficacy of tactile stimulation on visual memory, people with left hand as a dominant should also be participating in this study. It helps in understanding how tactile stimulation affects the visual memory whether it improves or declines the visual memory performance of participants.

CHAPTER 6: CONCLUSION AND FUTURE RECOMMENDATION

6.1 Conclusion

The ability to recognize, store, and recall visual information is a crucial cognitive capacity that is necessary for everyday functioning and decision-making. Learning, navigating, and solving problems are just a few of the everyday skills that are supported by effective visual memory. Visual memory challenges can have a detrimental effect on social, professional, and academic performance in addition to perhaps causing more general cognitive and psychological issues. It is hypothesized that techniques include auditory circumstance, training activities, and tactile circumstance can improve visual memory function. Nevertheless, there is still ongoing research into the brain mechanisms highlighting these strategies and how well they work to enhance visual memory.

The main objective of this study was to evaluate the effect of tactile stimulation on visual memory performance and assess whether the tactile circumstances can be a non-pharmacological way for improving visual memory. For this purpose, tactile vibration of low and high frequency vibration was provided to participants. The participant's performance was evaluated by a visual assessment task. All participants were university students aged between 18 to 26 years.

Multiple statistical analysis tests have been conducted on the collected data. Analysis of Variance (ANOVA) test has been performed to examine the effect of tactile stimulation on visual memory performance. The results show there is a significant difference in assessment test scores between no stimulation, low frequency stimulation and high frequency stimulation. This emphasized the importance of tactile stimulation for enhancing visual memory performance.

We also investigate how the sequence of tactile stimulation affects the visual memory. The statistical test results show there is no significant difference between sequence of tactile stimulation on memory performance. So, the improvement in memory performance is independent of sequence of stimulation.

Lastly a statistical analysis test has been performed on the data to assess is the visual memory of participants depends on the type of task. The results highlight that there is no significant effect of type of task on visual memory performance at low and high frequency vibrations.

6.2 Future Recommendation

In this study, the experimentation was performed on the university student of almost same level of education with no cognitive function impairment. The future the heterogenous sample should be selected. People with old age should be chosen to evaluate tactile stimulation effect on memory performance. Secondly, we use behavioral analysis, so in order to evaluate how brain response, how this tactile stimulation affects visual memory and what neural network is responsible for this integration between tactile stimulation and visual memory.

REFERENCES

1. Baddeley, A., *The episodic buffer: a new component of working memory?* Trends in cognitive sciences, 2000. **4**(11): p. 417-423.

2. Eichenbaum, H., *On the integration of space, time, and memory.* Neuron, 2017. **95**(5): p. 1007-1018.

3. Tulving, E., *Episodic memory: From mind to brain.* Annual review of psychology, 2002. **53**(1): p. 1-25.

4. Craik, F.I. and R.S. Lockhart, *Levels of processing: A framework for memory research.* Journal of verbal learning and verbal behavior, 1972. **11**(6): p. 671-684.

5. Cowan, N., *Short-term memory based on activated long-term memory: A review in response to Norris (2017).* 2019.

6. Tulving, E., *Elements of episodic memory*. 1983, Oxford University Press.

7. Cowan, N., *What are the differences between long-term, short-term, and working memory?* Progress in brain research, 2008. **169**: p. 323-338.

8. Sligte, I.G., et al., *Detailed sensory memory, sloppy working memory.* Frontiers in psychology, 2010. **1**: p. 175.

9. CROWDER, R.G., *Sensory memory systems*, in *Perceptual Coding*. 1978, Elsevier. p. 343-373.

10. Coltheart, M., *Iconic memory.* Philosophical Transactions of the Royal Society of London. B, Biological Sciences, 1983. **302**(1110): p. 283-294.

11. Kinukawa, T., et al., *Properties of echoic memory revealed by auditory-evoked magnetic fields.* Scientific Reports, 2019. **9**(1): p. 12260.

12. Wan, C., et al., *Artificial sensory memory.* Advanced Materials, 2020. **32**(15): p. 1902434.

13. Oberauer, K., et al., *Benchmarks for models of short-term and working memory.* Psychological bulletin, 2018. **144**(9): p. 885.

14. Cascella, M. and Y. Al Khalili, *Short-Term Memory Impairment*, in *StatPearls [Internet]*. 2024, StatPearls Publishing.

15. Tulving, E. and H.J. Markowitsch, *Episodic and declarative memory: role of the hippocampus.* Hippocampus, 1998. **8**(3): p. 198-204.

16. Squire, L.R. and S.M. Zola, *Structure and function of declarative and nondeclarative memory systems.* Proceedings of the National Academy of Sciences, 1996. **93**(24): p. 13515-13522.

17. Piccinin, M.A., J.H. Miao, and J. Schwartz, *Histology, meissner corpuscle.* 2018.

18. Talbot, W.H., et al., *The sense of flutter-vibration: comparison of the human capacity with response patterns of mechanoreceptive afferents from the monkey hand.* Journal of neurophysiology, 1968. **31**(2): p. 301-334.

19. Yonelinas, A., et al., *The role of recollection, familiarity, and the hippocampus in episodic and working memory.* Neuropsychologia, 2024. **193**: p. 108777.

20. Nuñez, A. and W. Buño, *The theta rhythm of the hippocampus: from neuronal and circuit mechanisms to behavior.* Frontiers in cellular neuroscience, 2021. **15**: p. 649262.

21. Estahbanati, M.F., et al., *The Effect of Involuntary Tactile Stimulation on the Creativity and Rey Auditory-Verbal Memory of Young Adults.* Basic and Clinical Neuroscience, 2022. **13**(6): p. 755.

22. Dehghan Nayyeri, M., M. Burgmer, and B. Pfleiderer, *Impact of pressure as a tactile stimulus on working memory in healthy participants.* PloS One, 2019. **14**(3): p. e0213070.

23. Guo, T., et al., *Improving visual working memory with training on a tactile orientation sequence task in humans.* SAGE Open, 2021. **11**(3): p. 21582440211031549.

24. Özkan, Ş., et al., *The Effect of Tactile Stimulation on Spatial Memory and Hippocampal Neuronal Density in Rats with Sensory Deprivation During a Critical Period.* Available at SSRN 4741610.

25. Bresciani, J.-P., F. Dammeier, and M.O. Ernst, *Vision and touch are automatically integrated for the perception of sequences of events.* Journal of vision, 2006. **6**(5): p. 2-2.

26. Oroszi, T., et al., *Whole body vibration improves spatial memory, anxiety-like behavior, and motor performance in aged male and female rats.* Frontiers in aging neuroscience, 2022. **13**: p. 801828.

27. Ide, M. and S. Hidaka, *Tactile stimulation can suppress visual perception.* Scientific reports, 2013. **3**(1): p. 3453.

28. Suk, H.-J., et al., *Vibrotactile stimulation at gamma frequency mitigates pathology related to neurodegeneration and improves motor function.* Frontiers in Aging Neuroscience, 2023. **15**: p. 1129510.

29. Campbell, E.A., et al., *Tactile low frequency vibration in dementia management: a scoping review.* Frontiers in Psychology, 2022. **13**: p. 854794.

30. de Los Angeles, G.A.M., et al., *Tactile stimulation effects on hippocampal neurogenesis and spatial learning and memory in prenatally stressed rats.* Brain Research Bulletin, 2016. **124**: p. 1-11.

31. Sörös, P., et al., *Functional MRI of working memory and selective attention in vibrotactile frequency discrimination.* BMC neuroscience, 2007. **8**: p. 1-10.

32. Spitzer, B., E. Wacker, and F. Blankenburg, *Oscillatory correlates of vibrotactile frequency processing in human working memory.* Journal of Neuroscience, 2010. **30**(12): p. 4496-4502.

33. Ryun, S., et al., *Tactile frequency-specific high-gamma activities in human primary and secondary somatosensory cortices.* Scientific reports, 2017. **7**(1): p. 15442.

34. Chung, Y.G., et al., *Frequency-dependent patterns of somatosensory cortical responses to vibrotactile stimulation in humans: A fMRI study.* Brain research, 2013. **1504**: p. 47-57.

35. Kim, M.-Y., et al., *Vibration alert to the brain: evoked and induced MEG responses to high-frequency Vibrotactile stimuli on the index finger of dominant and non-dominant hand.* Frontiers in human neuroscience, 2020. **14**: p. 576082.

36. Koenig, S.D., *Remembering What We've Seen: The Hippocampus and Relational Memory*. 2017.

37. Wynn, J.S., Z.-X. Liu, and J.D. Ryan, *Neural correlates of subsequent memory-related gaze reinstatement.* Journal of cognitive neuroscience, 2022. **34**(9): p. 1547-1562.

38. Popov, T. and T. Staudigl, *Cortico-ocular coupling in the service of episodic memory formation.* Progress in Neurobiology, 2023. **227**: p. 102476.

39. Göschl, F., et al., *Oscillatory signatures of crossmodal congruence effects: An EEG investigation employing a visuotactile pattern matching paradigm.* Neuroimage, 2015. **116**: p. 177-186.

40. Ku, Y., et al., *Sequential roles of primary somatosensory cortex and posterior parietal cortex in tactile-visual cross-modal working memory: a single-pulse transcranial magnetic stimulation (spTMS) study.* Brain stimulation, 2015. **8**(1): p. 88-91.

41. Veale, J.F., *Edinburgh handedness inventory–short form: a revised version based on confirmatory factor analysis.* Laterality: Asymmetries of Body, Brain and Cognition, 2014. **19**(2): p. 164-177.

42. Ransil, B.J. and S.C. Schachter, *Test-retest reliability of the Edinburgh Handedness Inventory and Global Handedness preference measurements, and their correlation.* Perceptual and motor skills, 1994. **79**(3): p. 1355-1372.

43. Syakiylla Sayed Daud, S.N., R. Sudirman, and C. Omar, *Features of Brain Rhythms During the Visual Memorizing Task and Auditory Stimuli Using Electroencephalography.* Malaysian Journal of Medicine & Health Sciences, 2022. **18**.

44. Daud, S.N.S.S. and R. Sudirman, *Pattern of EEG voltage and oscillations under stimulation of Mozart's music and white noise for visual learning process.* Biomedical Signal Processing and Control, 2023. **85**: p. 104986.

45. Daud, S.N.S.S. and R. Sudirman, *Effect of audiovisual stimulation on adult memory performance based electroencephalography wavelet analysis.* Biomedical Signal Processing and Control, 2022. **76**: p. 103659.

46. Zhang, X., et al. *A study of different background language songs on memory task performance*. in *2009 international symposium on intelligent ubiquitous computing and education*. 2009. IEEE.

47. Breitwieser, C., et al., *Stability and distribution of steady-state somatosensory evoked potentials elicited by vibro-tactile stimulation.* Medical & biological engineering & computing, 2012. **50**: p. 347-357.

48. Chu, C., et al., *A P300 brain-computer interface paradigm based on electric and vibration simple command tactile stimulation.* Frontiers in Human Neuroscience, 2021. **15**: p. 641357.

49. GUAN, L., W. LUO, and J. HAN, *The modality shifting effects in the multisensory integration paradigm.* Advances in Psychological Science, 2022. **30**(5): p. 1018.

50. Tan, G., et al., *Does vibrotactile stimulation of the auricular vagus nerve enhance working memory? A behavioral and physiological investigation.* Brain Stimulation, 2024. **17**(2): p. 460-468.

51. Caclin, A., et al., *Tactile "capture" of audition.* Perception & psychophysics, 2002. **64**: p. 616-630.

52. Spence, C., *Crossmodal spatial attention.* Annals of the New York Academy of Sciences, 2010. **1191**(1): p. 182-200.

53. Burton, H., R.J. Sinclair, and D.G. McLaren, *Cortical network for vibrotactile attention: a fMRI study.* Human brain mapping, 2008. **29**(2): p. 207-221.

54. Van Boven, R.W., et al., *Tactile form and location processing in the human brain.* Proceedings of the National Academy of Sciences, 2005. **102**(35): p. 12601-12605.

55. Zhang, M., et al., *Tactile discrimination of grating orientation: fMRI activation patterns.* Human brain mapping, 2005. **25**(4): p. 370-377.

56. Seri, F.A.S., et al., *Investigating cortical networks from vibrotactile stimulation in young adults using independent component analysis: an fMRI study.* Neuroscience Research Notes, 2023. **6**(3): p. 194.1-194.15.