Auditory spatial attention through transcranial direct current stimulation in bilinguals

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Dedicated to my exceptional parents and adored siblings whose tremendous support and cooperation led me to this wonderful accomplishment.

And to myself, for the perseverance and determination that have carried me through this journey.

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I am profoundly thankful to my beloved parents, who raised me when I was not capable of walking and have continued to support me at every step of my life.

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tDCS	Transcranial direct current stimulation
EEG	Electroencephalography
PPC	posterior parietal cortex
mA	milliAmperes
pIFG	posterior inferior frontal gyrus
L1	First language
L2	second language
STG	Superior temporal gyrus
Mic	Microphone
dB	Decibel
IPS	intraparietal sulcus

ABSTRACT

Bilingualism enhances cognitive flexibility, executive functioning, and attention, but can lead to challenges like smaller vocabulary and reduced verbal fluency. Bilinguals often struggle with speech recognition in noisy environments, particularly in their non-native language. Neuroplastic adaptations from bilingualism alter brain anatomy, though the extent and implications of these changes are still not fully understood. The aim of the study was to investigate the effects of anodal transcranial direct current stimulation (tDCS) on language comprehension focusing on native Urdu (L1) and second language English (L2) in bilingual individuals, considering proficiency levels. Fifty healthy subjects participated in this randomized, single-blinded, and single session study involving an Active and Control groups. Stimuli consisted of 88 sentences presented in 2 blocks the subjects performed three sessions including practice session of 2 mins followed by pre-tDCS session of 7 minutes,20 minutes of offline active tDCS /no stimulation and 7 minutes of post tDCS session, with performance evaluated based on key words identified from target sentences. A two-way repeated measures ANOVA was used for the analysis. The analysis of variance (ANOVA) results comparing pre- and post-intervention scores revealed significant improvements in both the Active and Control groups. We found that tDCS enhanced auditory spatial attention with greater impact on the dominant language, especially among those with higher proficiency level ($p<0.05$). Control group also showed improvements in both languages. The cross-linguistic effects observed indicate that tDCS may facilitate language transfer between bilinguals. These findings suggest pathways for further investigation of tDCS in language learning and rehabilitation, particularly in multilingual environments.

Key Words: anodal tDCS, left posterior inferior frontal gyrus, auditory spatial attention, bilingual, language comprehension

CHAPTER 1: INTRODUCTION

1.1 Background

Both humans and many other creatures that can hear are incredibly skilled. Even in busy situations, they are able to distinguish and focus on certain sounds. This extraordinary capacity is commonly referred to as the "cocktail-party effect." Imagine yourself at a party where there are a lot of people chatting, music is playing, and other sounds. You are able to concentrate on a single discussion in spite of all this noise. This ability is essential for both communicating and comprehending our environment, but for a very long-time scientists were unsure of how our brains managed to accomplish this. They knew rather well how we find a single sound in a quiet environment, but how we manage to select out a single sound in a busy, noisy environment remained a mystery. Scholars have recently begun to investigate how our brains process situations of this nature in not

Figure 1.1: Cocktail party

only humans but also in other creatures such as frogs, insects, and birds. They seek to comprehend the intricacies of how our sense of hearing functions in authentic situations, such as a boisterous gathering or a cacophonous setting [1].

Many noises combine in regular settings before they reach our ears. When there is a lot of noise around, our brain uses spatial attention, which is like its superpower, to help us distinguish and select the particular sound we want to focus on. It's similar to identifying the tune of a song in a crowded setting or picking out one specific voice among many. This ability enables us to tune out the distracting background noise and focus on what really important [2]. This is called Spatial attention or cocktail party. Spatial attention can be auditory or visual. There are many brain areas of brain which are controlling visual and auditory spatial attention.

It is well known that a unique network in our brains allows us to focus on objects inside our visual field known as the "dorsal attention network," it is composed of several regions of our cortex's frontal and parietal portions. Together, these brain areas enable us to explore our environment and concentrate on particular visual information. This network essentially functions as a group of brain areas working together to direct our attention and perception in the visual domain [3][4]. Auditory spatial attention is controlled by different areas of brain like Dorsolateral prefrontal cortex, superior temporal gyrus, Inferior posterior gyrus, planum temporal, superior frontal sulcus, left inferior frontal and pre- and postcentral areas, right posterior temporal cortex. The way our brainstem reacts to complex sounds gives us insight into how life experiences, like learning a second language, becoming proficient in music, or being fluent in our original tongue, shape the auditory system's natural sound processing [5].

The human brain is really designed to learn many languages, as evidenced by the fact that bilingual and multilingual people have brains that have evolved to support more than one language. More individuals are becoming multilingual or bilingual as a result of globalization, making bilingualism the norm rather than the exception. If a person speaks one language then he/she is called monolinguist. Bilingual person is the one who can speak two languages and multilingual is the one who can speak multiple languages. A bilingual person may acquire a new language in response to educational requirements, immigration, or other circumstances, and may use both languages in various settings and at varying degrees of skill. According to this definition, a person who is bilingual may have learned a second language (L2) later in life in addition to having mastered both languages from birth or an early age. The various conditions and settings of second language learning have a significant impact on how multiple languages are organized in the brain. Furthermore, a bilingual or multilingual speaker may ultimately run into issues with potential conflicts between the languages they have learned, such as how to communicate in one language while preventing possible intruders from speaking in the other [6]. Scientists are working on finding the areas responsible for spatial attention in bilinguals. In today's world, speaking many languages is common. It is estimated that about half of the world's population is bilingual, with over 20% of individuals speaking more than one language in the United States alone. The desire for a more multilingual society has impacted public policy and education as a result of this expanding tendency.

Individuals who engage in multilingual interactions, particularly those who are not native speakers, come across a varied linguistic and auditory environment that is distinct from that of monolingual speakers. Because they are using two different language systems, bilinguals must control, modify, and conceal many streams of lexical information. Because of this balancing act, bilinguals—as opposed to monolinguals—develop more effective inhibitory control. The brain experiences both functional and anatomical changes as a result of the higher cognitive demands of learning two languages. Advantages in behaviors such as executive functioning, conflict monitoring, and sustained concentration are brought about by these alterations. It's interesting to note that lifetime multilingual experiences might boost cognition by building a "cognitive reserve," which may prevent cognitive deterioration later in life.

The brain can only hold so much information, therefore even while bilingualism offers many benefits, there can be drawbacks. For example, as compared to their monolingual colleagues, bilinguals may have a lesser vocabulary and have impairments in verbal fluency. These results imply that whereas bilingualism improves some skills, it could have negative effects on other equally vital roles. It is believed that both temporal and frontal MMN sources contribute to normal speech perception; sources in the inferior frontal gyrus (IFG) likely reflect higher-order (i.e., linguistic) analysis of speech information downstream, while sources in the superior temporal gyrus (STG) are thought to be involved in initial sound analysis in auditory sensory cortex Relevant to the current findings, earlier research has demonstrated that while listening to unclear or noise-degraded speech, inferior frontal sources (proximal to Broca's region and the insula) exhibit exceptional sensitivity. Other than these areas they are also other areas controlling Bilingual auditory spatial attention [7]. These areas include Dorsolateral prefrontal cortex, Cerebellum, STG, superior prefrontal frontal gyrus etc.

1.2 Scope and Motivation

It's vital to understand that bilingualism exerts a heavy load on the cognitive system, even if bilinguals may make learning a second language appear straightforward. Studies have indicated that as a result of neuroplastic adaptation, bilingualism can alter neuronal processing and alter the anatomy of the brain. But it's unclear how these changes have developed and what their implications are or how much they have changed and how can they be enhanced. This is important for communication, social interactions. If someone who is not efficient in distinguishing between languages and noise, this makes his/her social interaction different. Enhancement and improvement of auditory spatial attention in bilingual is not done so far.

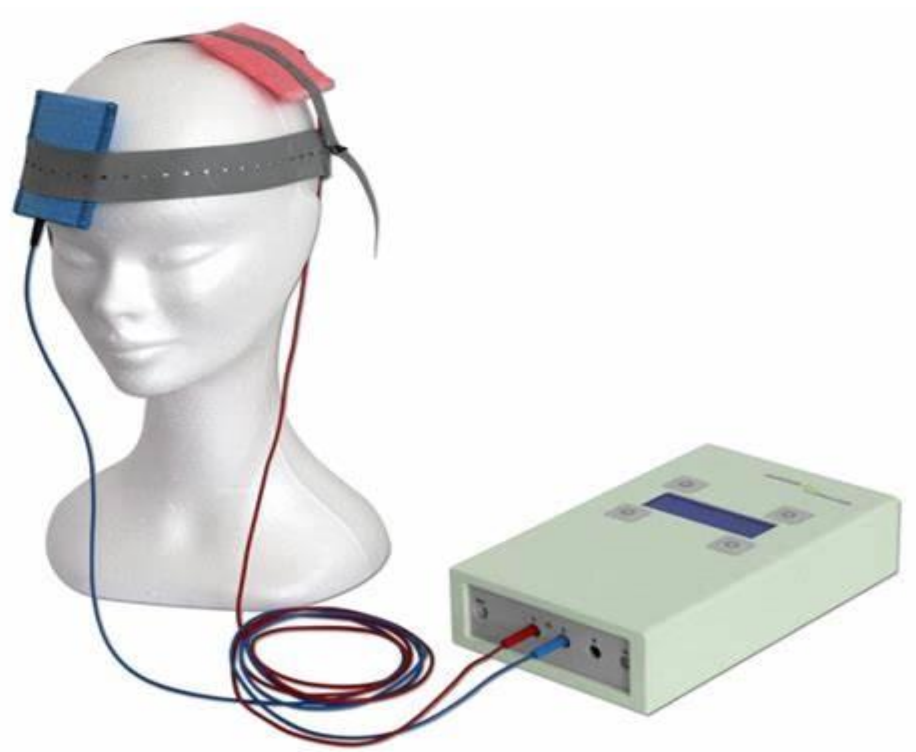


Figure 1.2: Transcranial direct current stimulation

am working on the enhancement of auditory and improvement of auditory spatial attention in bilinguals by stimulating posterior inferior frontal gyrus(pIFG) through tDCS. Transcranial electrical current stimulation is one kind of brain stimulation that can help people with aphasia, language processing disorders, stroke, motor and cognitive deficiencies, and other clinical conditions regain their ability to execute cognitive processes [8].

1.3 Objectives of the study

The objective of the project aims to explore how anodal transcranial Direct Current Stimulation (tDCS) influences language comprehension in individuals who are bilingual. Anodal tDCS involves applying a low electrical current to the brain's surface through electrodes. The study is interested in understanding whether this stimulation has a discernible effect on how bilingual individuals comprehend language. The focus here is on assessing whether the impact of anodal tDCS varies when participants are exposed to targets in their native language (Urdu) compared to their second language (English). This investigation involves tasks or tests designed to evaluate comprehension skills in both languages, considering potential differences in how the brain processes the native and second languages under the influence of tDCS.

It includes a thorough analysis of participants' responses to language targets in both Urdu and English. The study intends to find any discrepancies or trends in the way anodal tDCS influences language processing by comparing participants' comprehension skills with native and second languages independently. This evaluation can shed light on whether the stimulation has a language-specific effect and whether individuals who are bilingual react differently to the intervention depending on which language they are processing.

CHAPTER 2: LITERATURE REVIEW

2.1 Spatial attention

The term "selective attention" generally refers to the processes that determine which among several potential inputs will be examined beyond the level where all inputs could be processed simultaneously. Over the past four decades, there have been various changes in how selective attention is conceptualized, starting with Broadbent's initial proposal.

Initially, early theories likened selection to a filtering mechanism operating based on early perceptual or later semantic criteria. However, later theories shifted the perspective, portraying attention as the selective distribution of a limited supply of cognitive resources. This changed the view of attention from being a discrete gateway that separates different processing levels to a modulatory influence capable of enhancing or reducing the efficiency of demanding processing tasks.

This new perspective on attention makes it a more adaptable mechanism, able to facilitate or inhibit the processing of input. It also allows for an analysis of selection phenomena in terms of costs and benefits. For instance, improving the efficiency of processing a selected part of input comes at the expense of decreasing the processing of other non-selected portions of input [9]. There can be spatial visual attention and spatial auditory attention.

2.2 Spatial visual attention

When people undergo a vision test, the common practice involves reading letters on an eye chart. However, seeing things goes beyond just recognizing the shapes of letters. To truly examine a specific item, like identifying it and noting its features and actions, the first step is to distinguish or "individuate" it. Individuation is a fundamental aspect of attention, and it serves various functions in perception. For instance, individuating an item is essential for encoding its location accurately and keeping track of its position over time. Individuation becomes essential when dealing with sets containing more than four items.

The image in Fig. 2.1 helps clarify the difference between resolving and individuating items. It's relatively straightforward to visually recognize all the items in this display. For instance, fixating on the cross, the vertical lines in the patch on the right are easily distinguishable—they are all vertical, parallel, thin, and black. However, when attempting to focus on the fourth line from fixation while still fixating on the cross, you might find it challenging to pick out this specific item with attention alone. This demonstration underscores the difficulty in isolating and examining individual items, even when they are visually resolvable, particularly in the context of the 'crowding' effect [10].

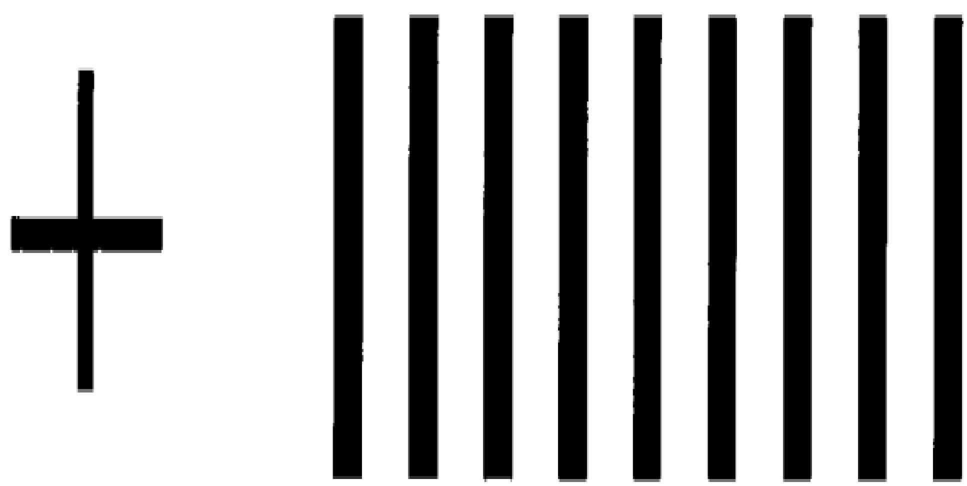


Figure 2.1: Simple demonstration which shows the difference between visual acuity and attention**.**

In simple terms, attention is an internal state that can quickly change based on instructions. This implies that people react differently to the same stimulus depending on their current attentional state. Spatial attention, on the other hand, involves focusing on a specific area where performance in a task is better compared to areas outside of that focus. It essentially means that directing attention to a particular region can enhance how well one performs in a given task within that chosen area [11].

2.3 Brain areas controlling spatial visual attention

The available evidence from both monkey physiology and human neuroimaging studies suggests that spatially selective attention has a significant impact on processing in the visual system. Specifically, when attention is directed to a particular location in the visual field, neural responses to stimuli at that location are more pronounced compared to responses at ignored locations. These modulatory signals are thought to originate from higher-order areas in the frontal and parietal cortex, including the superior parietal lobule (SPL), intraparietal sulcus (IPS), frontal eye fields (FEF), and supplementary eye field (SEF), and are transmitted back to the visual system.

However, the precise mechanism by which the frontoparietal network controls the allocation of attention across the visual field remains largely unknown. Models of spatial attention control have emerged from studying patients with visuospatial hemineglect, a condition where individuals struggle to direct attention to the contralateral visual field. One theory, Heilman's "hemispatial" theory, suggests that the right hemisphere (RH) directs attention to both visual hemifields, while the left hemisphere (LH) directs attention to the right visual field (RVF) only. Another theory, Kinsbourne's "interhemispheric competition" theory, proposes an opponent processor control system in which each hemisphere directs attention toward the contralateral visual field and is balanced through reciprocal inhibition.

Despite their differences, both theories predict that higher-order cortex contains discrete representations of visual space involved in controlling attention throughout the visual field. In the human brain, topographically organized areas have been identified in frontal cortex (FEF, precentral cortex/inferior frontal sulcus) and posterior parietal cortex (IPS1–IPS5, SPL1), which align with known activations of the frontoparietal attention network. The researchers hypothesized that these topographic frontoparietal areas might form part of a distributed higher-order control system for spatial attention [12]. The idea that paying attention to specific locations in our vision is more associated with the right side of the brain has been a common belief. This belief was largely based on studies with patients who have difficulty perceiving things on one side of their vision, particularly after damage to the right side of the brain.

However, when scientists looked at brain activity in healthy individuals using brain imaging, the results were not as straightforward. Some studies suggested that the right side of the brain might be more involved in certain attention tasks, but later research showed that both sides of the brain seem to work together when it comes to paying attention to different parts of our visual field.

The way we naturally shift our attention to important things in our environment, especially when triggered by something important but not directly focused on, seems to involve both sides of the brain. This challenges the idea that one side is dominant in controlling our attention. It's essential to note that previous conclusions about which side of the brain is more involved in attention were criticized because the comparisons between the two sides were not always done properly.

In summary, while some theories suggested the right side of the brain might be more important for attention, recent research emphasizes that both sides of the brain work together for various attention-related tasks, and this study aimed to provide more solid evidence for this understanding [13].

2.4 Spatial auditory attention

In places where there's lots of noise, like busy streets or crowded places, different sounds mix together before we hear them. Paying attention to where a sound is coming from becomes really important. It helps us pick out the sound we want to hear, like someone talking, while ignoring all the other noise around us. Studies by Best, Kidd, and Shinn-Cunningham have shown that this ability to focus on specific sounds improves our listening experience in noisy places [14]. Think about being at a busy party where lots of sounds, like glasses clinking and people talking, mix together before reaching your ears. To enjoy your friend's story, you have to block out the background noise and concentrate on her voice. But, being aware of those other sounds is still important for understanding what's happening around you. Sometimes, the noise you ignored might suddenly become interesting, like when you realize the person next to you is sharing some gossip about your boss. Being able to both concentrate and switch your attention when needed helps you navigate social situations successfully. This is known as Cocktail party or spatial auditory attention [15]. Directing our attention to specific places that matter to our goals is crucial for smart decision-making. However, our attention must also be ready to quickly shift to another spot in response to unexpected sounds that might indicate opportunities or dangers. This ability to focus and switch attention is vital for survival, as it allows us to respond promptly to things in the environment that require immediate action. Sounds are particularly effective at grabbing our attention in this way, and the responses to auditory cues are similar across different species. Interestingly, auditory stimuli tend to have a stronger alerting effect on attention than visual cues in tasks that involve focusing attention [16].

Even when there's a lot of noise, like at a party with many people talking, humans are really good at focusing on one particular sound or voice. We can pick out and pay attention to a specific conversation, ignoring the other background noises. This impressive skill, known as the "cocktail party effect," helps us have meaningful conversations and stay connected even in noisy places. Scientists are interested in understanding how our brains manage to do this so well [17].

2.5 Brain areas controlling spatial auditory attention

In the study, researchers discovered attention-related activity in areas beyond just hearing in the brain. They found that theta waves played a key role in how attention influenced the auditory cortex. Both left and right hemispheres of the brain were involved in attention networks, showing functional issues on both sides and structural problems specifically in the left hemisphere, even though individuals with First Episode Psychosis (FEP) maintained intact connections between theta and gamma brain waves in the auditory cortex. These new insights suggest early attention-related issues in the brain during psychosis, opening the possibility for future non-invasive treatments [18].

While both hearing and vision provide spatial information about the surroundings, our understanding of how auditory spatial cognition works is less comprehensive than visual spatial cognition. The human cortex has over 20 visual spatial map representations, yet no known auditory spatial maps have been reported. The intraparietal sulcus (IPS) in the brain, known for visual spatial maps supporting attention and short-term memory, has not been shown to contain auditory spatial maps. This study reveals that specific regions within the superior parietal lobule, part of the IPS, are recruited during auditory spatial tasks, supporting the idea of multisensory spatial processing in certain areas of the brain [19].

The study, using brain scans, explored how we focus on sounds, discovering a key area in the middle-upper brain involved in auditory spatial attention. This region activated during tasks guiding attention to auditory cues. Before hearing a sound, increased activity in the auditory sensory cortex hinted at preparation for expected stimuli. Common areas in the frontal and parietal regions for both visual and auditory attention were identified, suggesting shared neural processes. [20].

The research found that when paying attention to sounds on the right side, the left side of the brain's auditory cortex was more active, and vice versa. This suggests that the brain fine-tunes its auditory processing based on where attention is directed. Increased activity was noticed in the frontal cortex when focusing on auditory stimuli, suggesting that this part of the brain plays a role in managing the selective tuning of auditory attention [21]. Our results show a double dissociation between the involvement of right temporoparietal junction (RTPJ) and the left inferior parietal supramarginal part (LIPSP) in tasks requiring listeners to switch attention based on space and pitch features, respectively, suggesting that switching attention based on these features involves at least partially separate processes or behavioral strategies [22].

In this study, they examined the event-related potential (ERP) component ADAN, associated with frontal-lobe control during auditory spatial attention. While typically linked to frontal control, ADAN is often absent in auditory tasks. They tested the hypothesis that ERP activity related to frontal-lobe control in auditory spatial attention is distributed bilaterally. Comparing ERPs from attention-directing and neutral cues in a unimodal auditory task revealed an initial bilateral prefrontal positivity and a later parietal negativity. The frontal positivity likely reflects frontal-lobe attentional control, while the subsequent negativity suggests anticipatory biasing in the auditory cortex [23].

2.6 Improvement of Spatial attention

This study explored how natural variations in menstrual cycle hormones affect early cortical processing during spatial attention tasks. Higher progesterone in the luteal phase correlated with increased event-related potential (ERP) and alpha amplitude, suggesting enhanced attentional modulation. Cerebral asymmetry in the alpha frequency band was observed in luteal women. Early follicular women showed slower responses to right hemifield targets, indicating hormonal influences on visual target categorization [24]. The study investigated how electrical macrostimulation of the frontal eye fields (FEF) affects spatial attention in monkeys. Monkeys, when subjected to FEF stimulation, showed enhanced sensitivity to target luminance changes in the visual field region represented by the stimulated neurons. The degree of improvement depended on the timing of stimulation relative to the target event, with the most significant effect observed during temporal overlap. These findings suggest that FEF, involved in saccadic eye movements, contributes to transient improvements in spatial attention deployment [25]. Other than these, spatial attention can be improved through tDCS.

2.7 Transcranial direct current stimulation(tDCS)

Transcranial electric current stimulation is one of the brain stimulation techniques, which can improve performance of cognitive functions in humans and recover the clinical condition of different kinds of patients like aphasia, language processing, stroke, motor and cognitive deficits [26]. It emerges that humans can significantly gain from the easy-to-apply and affordable procedure [27]. The tES affects the neuronal states via the application of current waveforms transcranial. The forms of tES includes Transcranial pulsed current stimulation, Transcranial direct current stimulation, Transcranial random noise stimulation, and Transcranial alternating current stimulation. These forms of current are considered well-tolerated and operate by inducing changes in the electric activity both outside and inside the neurons, altering the resting membrane potential and the as a result, modifying neuronal synaptic efficiency [28]. These alterations are not sufficient to stimulate action potentials but can produce disparity in the response threshold of neurons being stimulated [29]. As a non-invasive brain stimulation method that may affect cognitive processes, including attention, transcranial direct current stimulation, or tDCS, has attracted attention. Since the field is still in its beginning stages, not many researches have clearly examined the ways in which tDCS may impact various aspects of attention. tDCS-assisted investigation of attentional processes is still in the beginning stages [30].

The tES involves the administration of weak intensity current (1-2mA) by a stimulator, driven by a battery, between the two electrodes (cathode and anode), positioned on the targeted area of the brain. The electrodes are generally of square shape, conductive and large inserts of sponges are enclosed in it (saline-soaked, 20-35cm^2). The current reaches the targeted cortical area where the electrode is attached and the extra cortical layers to arrive at the cortex, thus modulating the membrane polarity of the targeted neurons with an area underlying neural tissue [31]. There are many types of tDCS which are used in the literature for the improvement of cognitive and attention related functions.

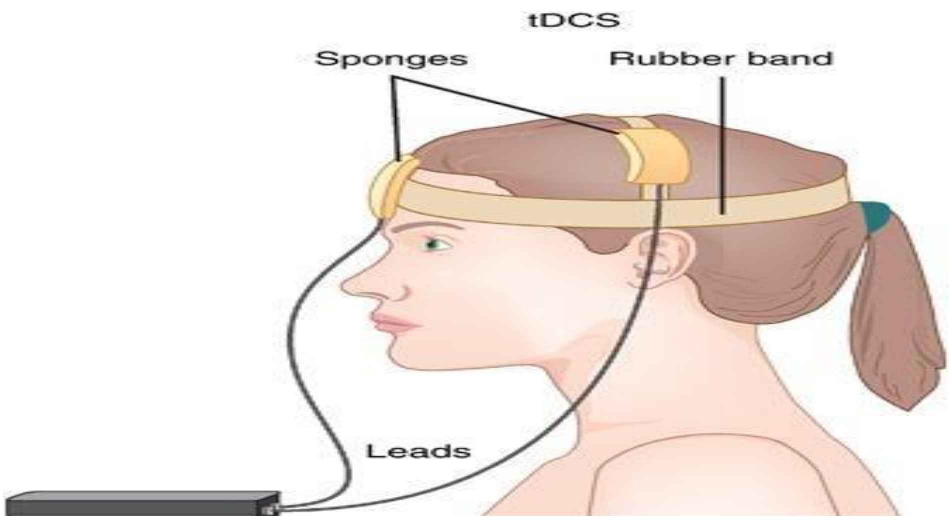


Figure 2.2: tDCS stimulation setup

2.7.1 Anodal tDCS

Positive and negative electrodes are used in their usual polarity. Anodal electrodes can improve memory, attention and other cognitive functions. Anodal tDCS over the left auditory cortex modulated auditory processing, leading to improved performance in tasks requiring spatial attention to auditory stimuli [33].

2.7.2 Cathodal tDCS

The electrode polarity is reversed in this case. Anode serves as a reference electrode and cathode is planted at the stimulation site. According to conventional knowledge, placing the anode over the target region causes an increase in excitability, while placing the cathode over the same region causes a decrease in excitability. This form of brain stimulation is thought to modulate the resting membrane potential of cortical neurons and, consequently, their excitability, depending on the polarity of the overlying electrode in relation to neuronal orientation [34].

However, various studies have reported positive effects of cathodal stimulation. Cathodal stimulation is reported to improve language comprehension in stroke patients [35]. Cathodal stimulation is also considered to improve attention and act as a noise filter to enhance cognitive performance [36]. It has also been reported that cathodal stimulation can prove successful results in treating migraine patients [37].

2.7.3 Sham tDCS

Sham stimulation session mainly serves as a control or for blinding purposes of tDCS experiments. In sham stimulation, current is ramped up and then down in just the start and end of the task so that participants can feel the itching sensation. The current intensity is the same; just the current duration is reduced to a total of about one minute or even less [38]. This stimulation is for short amount of time so there are no after effects [39].

2.7.4 Off-line and On-line tDCS

tDCS can also be characterized as off-line or on-line tDCS. They are mainly associated with the period of stimulation. If stimulation is provided when task is not being performed, either before or after the task, such type of stimulation is called off-line stimulation. Whereas, if tDCS is applied during the task performance then it is categorized as on-line tDCS stimulation.

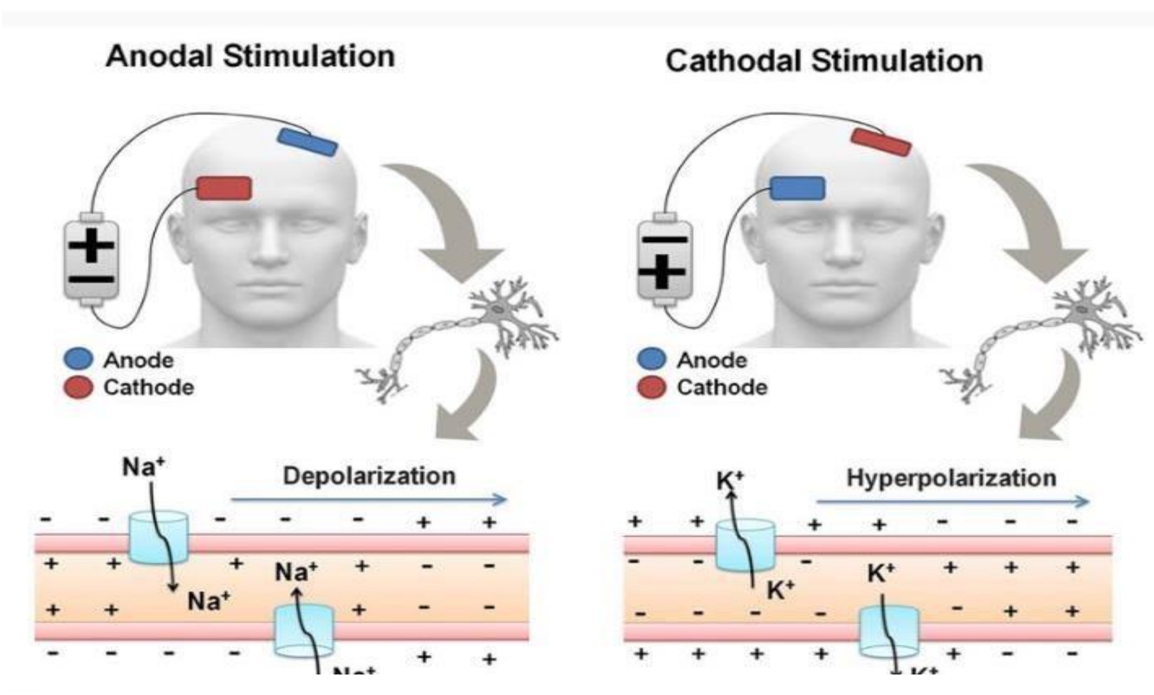


Figure 2.3: Effect of Anodal and Cathodal stimulation on membrane polarization.

2.8 Spatial Visual Attention through tDCS

The study explored if combining brain stimulation (tDCS) and cognitive training helps air traffic controllers. Active tDCS led to quicker responses, but not improved accuracy. Comparing with a sham group hinted at potential overall enhancement. The findings suggest increased brain activity may not always improve task performance. Customized tDCS protocols for air traffic control factors like attention demands are important [41].

Using photos that had been altered to include or remove target objects, the experiment evaluated participants' abilities to find hidden objects in complicated virtual environments. During training sessions, participants were given either 0.1 mA or 2.0 mA tDCS. Performance was evaluated both shortly after training and an hour later to look at retention. Measures of various aspects of attention were also obtained using the Attention Network Task (ANT). Higher tDCS currents were found to enhance alertness and detection performance [42].

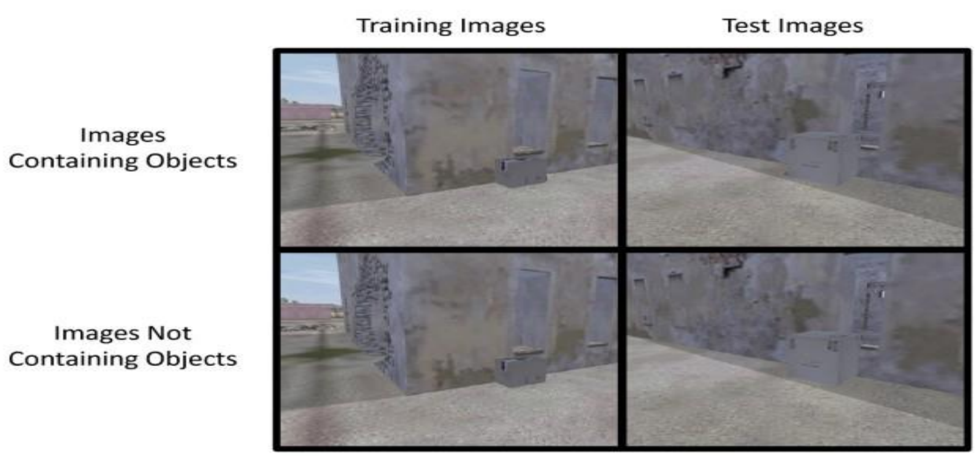


Figure 2.4: Object Detection Task Training and Test Stimuli. Examples of training (left) and test (right) stimuli are depicted.

2.9 Spatial Auditory Attention through tDCS

The study used a single-blind, sham-controlled crossover design with baseline and post-tDCS measurements, applying monopolar anodal and cathodal tDCS over the posterior temporal lobe. ERP correlates of "cocktail-party" localization, focusing on the N2 component, were analyzed using low-resolution electrical imaging. German one-syllable numbers ("eins," "vier," "acht," "zehn") were spoken by four native speakers (two males, mean pitch 141 Hz; two females, mean pitch 189 Hz). The experiment included 288 trials per block, with 72 target presentations at each of four positions and by each speaker, forming a subset of 576 combinations. Each trial lasted 3.125 seconds, totaling 15 minutes per block. The results have enhanced auditory spatial attention [43].

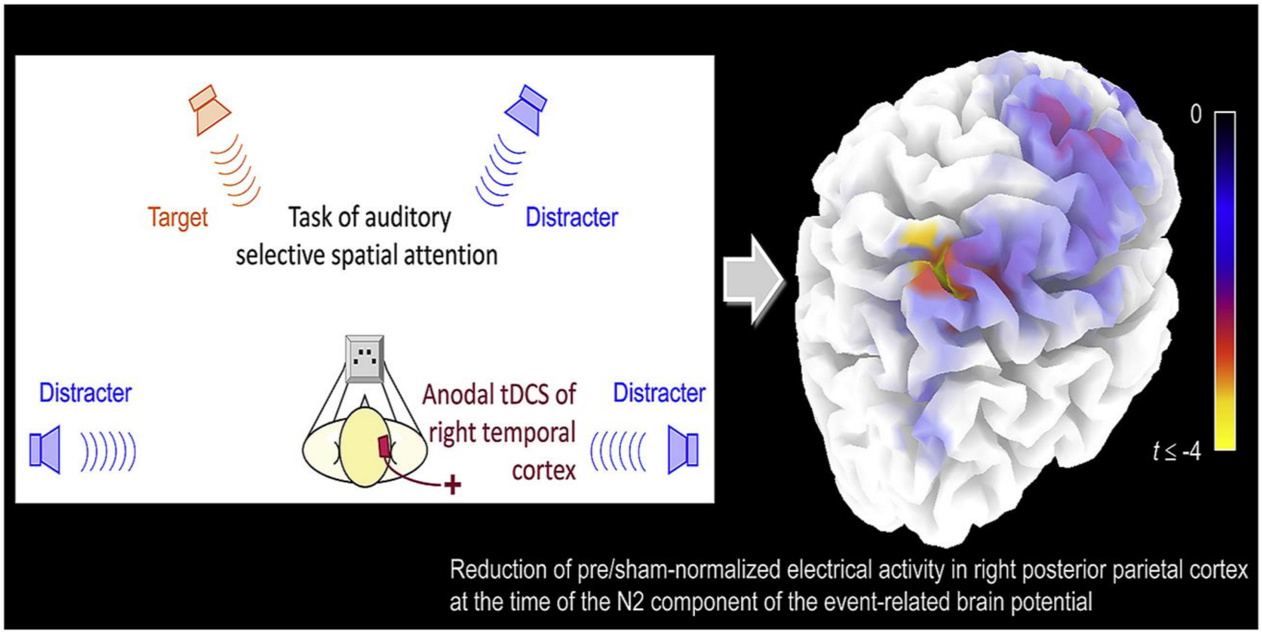


Figure 2.5: Monopolar anodal and cathodal tDCS over the posterior temporal lobe

This study tested tDCS's impact on temporal aspects of auditory processing in healthy subjects. Eleven subjects received 2mA bilateral anodal, cathodal, and sham tDCS over the auditory cortex, evaluated by the Random Gap Detection Test (RGDT). Statistical analysis showed significant interaction effects for 4000 Hz and clicks: anodal tDCS improved performance by 22.5% and 29.4% respectively, while cathodal tDCS decreased performance by 54.5%. These findings suggest tDCS's potential in modulating auditory processing and encourage further research in central auditory processing disorders [44]. A between-channel gap detection task was used in the study to evaluate temporal processing. Participants were able to distinguish between band-passed and wideband noise stimuli in terms of timing. Throughout sessions, anodal, cathodal, or sham tDCS was applied to the auditory cortex. In order to accurately assess auditory cortex reactivity, stimulation was used in a shielded room. In contrast to the unaffected right auditory cortex, stimulation of the left auditory cortex had a negative impact on perception of rapid acoustic changes. This demonstrates how well the left hemisphere processes fast temporal information from non-speech sounds [45]. tDCS can also spatial attention in monolinguals, bilinguals but there is less research on auditory spatial attention in bilinguals. Below are some researches related to this.

2.10 Spatial attention through tDCS in bilinguals

Participants of Spanish English Bilinguals received left anodal DLPFC stimulation, right anodal DLPFC stimulation, or sham stimulation before completing tasks. Tasks included a switching task, a picture-naming task for bilinguals, and an action-object task for both bilinguals and monolinguals. Cues were provided every 3-5 trials, and each trial lasted 1000 ms. These tasks were conducted following 20 minutes of 2 mA tDCS stimulation in the study. Left DLPFC stimulation enhanced accuracy in bilinguals' picture-naming task but elevated switch costs in the shape-color task, indicating its distinct involvement in linguistic and non-linguistic control processes for bilingual individuals [46]. During sessions, participants received transcranial Direct Current Stimulation (tDCS) for 20 minutes, either as anodal tDCS (active stimulation) or sham tDCS (control). This occurred while participants of English-French performed online tasks like verbal and non-verbal fluency before transitioning to offline tasks such as picture naming and word translation while EEG was recorded. The tDCS application aimed to explore its real-time effects on language processing and cognitive tasks. These results contradict the hypothesis that left DLPFC tDCS would enhance language or cognitive control in bilinguals [47]. Prior to and following transcranial direct current stimulation, participants completed tasks involving the naming of pictures and numbers (tDCS). Every task session lasted roughly forty-five minutes and included eighty-two trials. Anodal current increased to 2 mA during 30 seconds of active stimulation, remained there for 14 minutes, and then decreased over an additional 30 seconds. The 14-minute session began and ended with a 30-second ramp-up and ramp-down in sham conditions. Right cerebellum stimulation reduced language switching costs significantly; higher L2 proficiency correlated with stronger improvements in language switching following this stimulation [48]. The study looked into how language switching is impacted by brain stimulation.

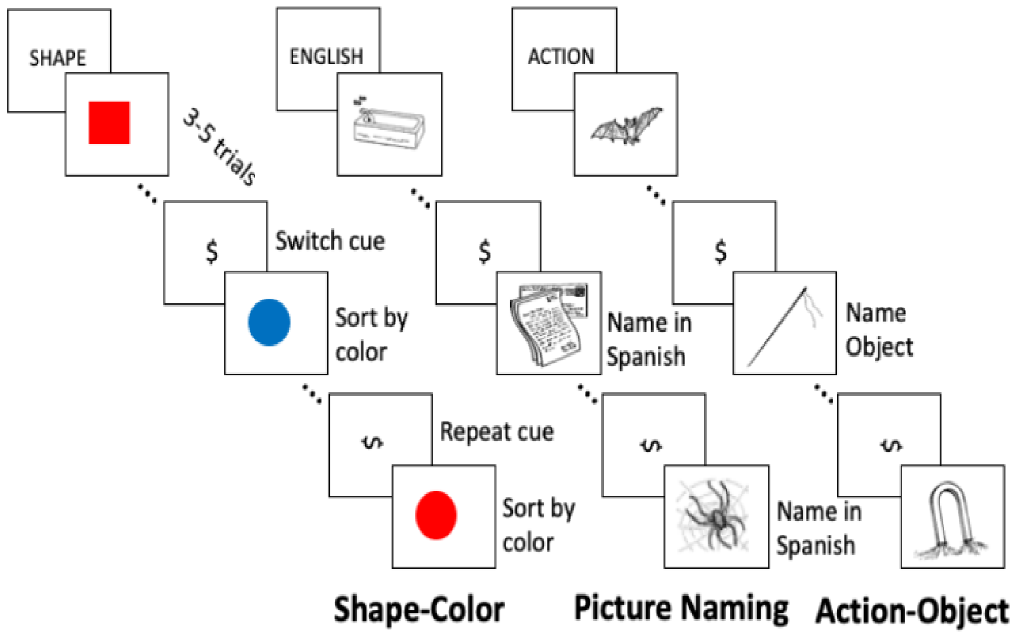


Figure 2.6: Switching task designs

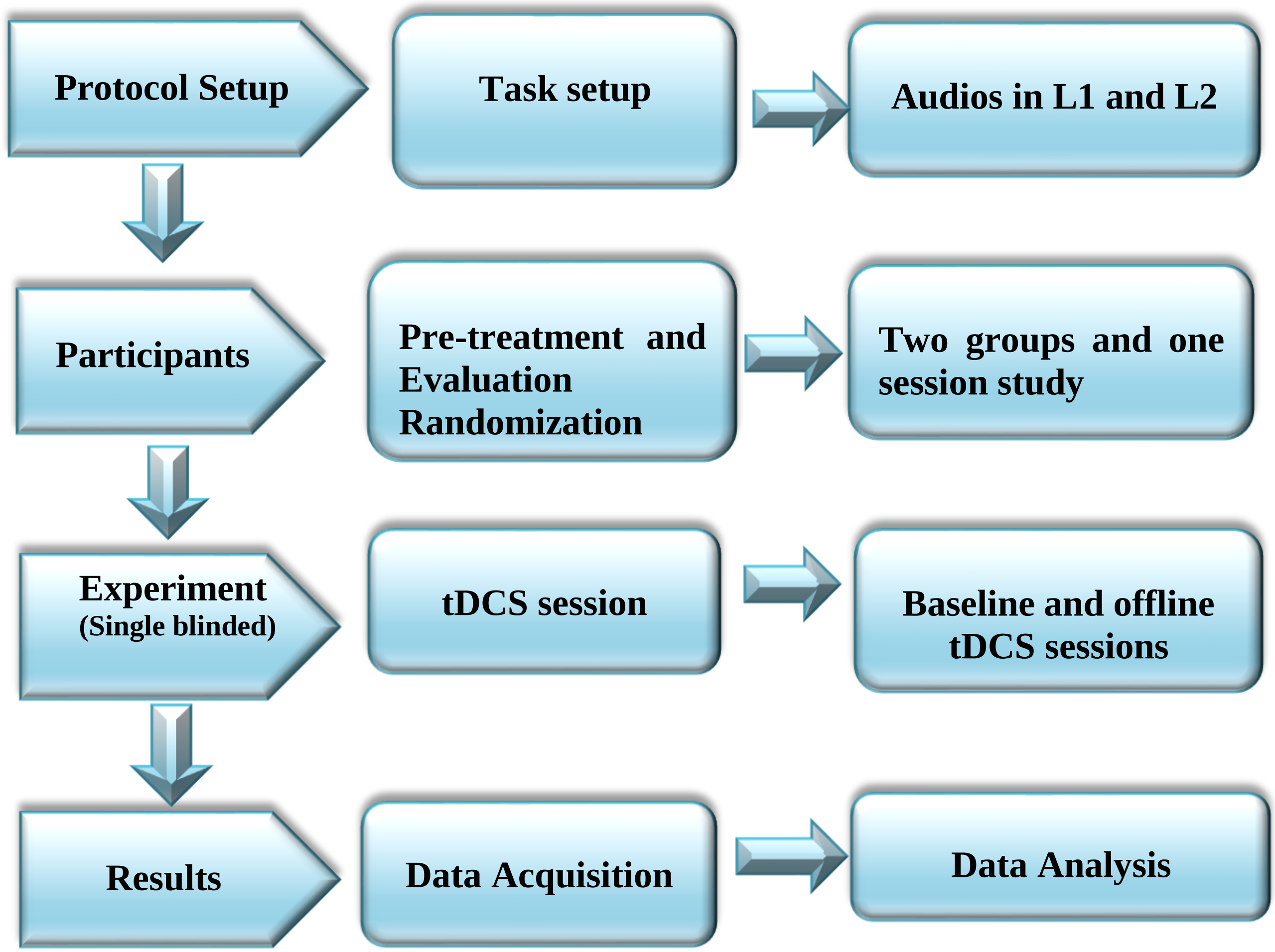
After brain stimulation, participants practiced naming pictures in two languages. Next, images on a computer screen were presented to them by the researchers. Every image featured a color cue that represented the naming language. Lastly, the participants gave the pictures names based on the language cue that matched them. According to the study, cathodal tDCS may facilitate language switching by strengthening the non-target language's inhibitory control [49].

After viewing standardized images, participants were asked to name them in two different languages. They went through anodal, cathodal, or sham brain stimulation to stimulate, inhibit, or control brain cells prior to naming. Participants were not informed of the type of stimulation they were receiving, and the order of stimulation was randomized. Measuring accuracy and reaction times, the researchers examined the impact of stimulation on language switching [50]. There is no work done so far on auditory spatial attention through tDCS in Bilinguals all works done so far are related to Visual spatial through tDCS in Bilinguals.

CHAPTER 3: MATERIALS AND METHOD

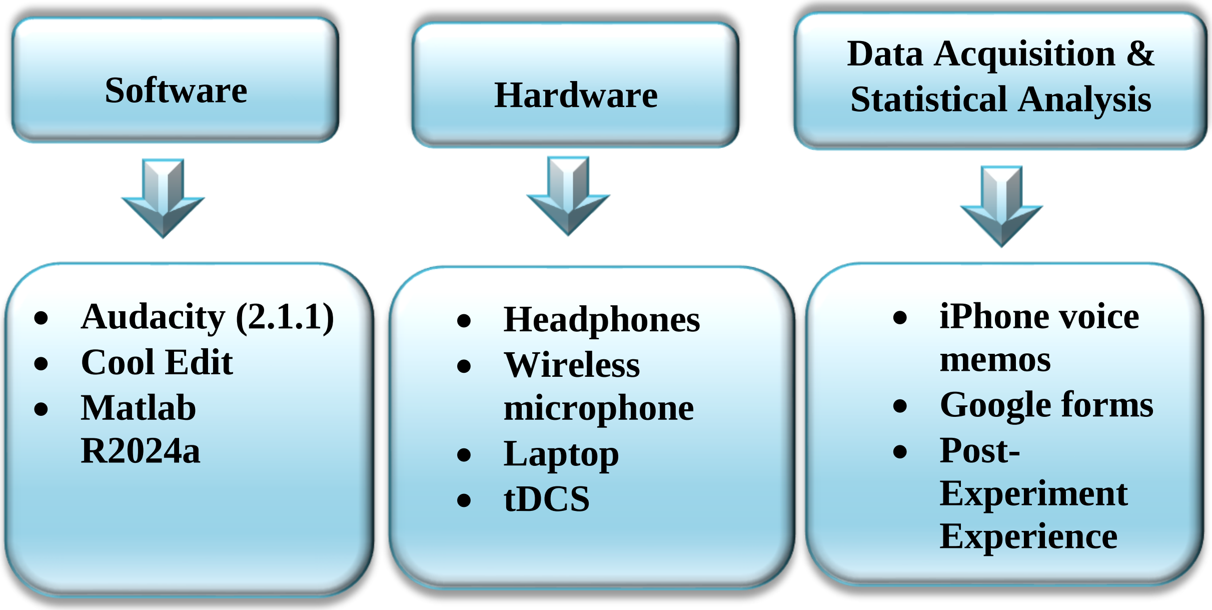
3.1 Study Protocol

A Single blinded, randomized active and offline tDCS controlled design is employed to investigate the effect of anodal tDCS targeting left inferior posterior frontal gyrus IFG (pIFG) in healthy Bilingual participants that tDCS will improve auditory spatial attention in them or not. An experimental task of auditory stimulations was designed to check the modulation. The data was acquired and analysis was done.



3.2 Setup and Software

The software and hardware which are used in my research are as follows



3.3 Materials

The materials which are used in my experiment are as follows:

3.3.1 Headphone

The A4TECH FH200i headphones feature a frequency response of 20Hz - 20kHz, 100dB sensitivity, and integrated noise cancellation, making them ideal for research. Their broad frequency range and high sensitivity ensure accurate sound reproduction, while noise cancellation enhances data accuracy by reducing ambient interference. These attributes make them suitable for audio experiments, data collection, and listening tests.

Figure 3.1: A4TECH FH200i headphones

3.3.2 Microphone

The YOOKIE wireless microphone, utilized for recording in our research, features a 2.4GHz frequency range, a signal-to-noise ratio of 60dB, and a response speed of 20ms.

Figure 3.2: YOOKIE wireless microphone

3.3.3 iPhone voice memos

The recordings for auditory spatial attention are made through voice memos of iPhone 7**.**

3.3.4 tDCS device

The tDCS is transcranial direction current stimulation device which can excited and deexcite the neuron**.** This device which was used in my research is a caputron based Activadose II Iontophoresis Deliver Unit, (https://www.caputron.com/transcutaneous-electrical-stimulation/333-activadose-ii-starterkit.html), a continuous current stimulator by means of a pair saline-soaked sponge electrodes. The maximum current is 4 mA. (current can be increased in steps of 0.1 mA from 0.1 mA to the maximum current.)

Figure 3.4: Activadose ii with the positive (red) and a negative (black) electrode

Figure 3.3: Electrodes

3.3.5 Electrodes

The electrodes which are used are square shaped rubber electrodes with an area of $25cm^2$.

3.3.6 EEG caps

The EEG caps which are used in research for locating targeting area on head are EASYCAP DE-82211 herrsching.

3.4 Task Setup

3.4.1 Sentence Selection and Translation

The study consists of sentences in three languages: Urdu, English, and Pahari. The English sentences were selected from the IEEE sentence database, commonly referred to as the Harvard sentences [51]. These sentences were then translated into Urdu and Pahari to create set of stimuli in all three languages.

3.4.2 Recording Procedure

Recordings of the English and Urdu sentences were made by a male speaker from NUST SMME, who is fluent in both languages. These recordings were used as the target sentences for the study. The masking effect in the background was created by mixing sentences in Urdu, English, and Pahari, recorded by a female speaker from NUST SMME, fluent in all three languages. The masker comprised pairs of sentences in different combinations: two English, Urdu-English, Urdu-Urdu, Urdu-Pahari, Pahari-Pahari, and Pahari-English.

3.4.3 Recording Equipment and Environment

The recordings were made using the iPhone Voice Memo application, utilizing the internal microphone. The iPhone was held 10-15 cm away from the speaker's mouth in a quiet room within the Prosthetic and Implantology lab SMME, NUST Islamabad. This setup ensured a consistent recording environment and high-quality audio capture.

3.4.4 *Audio Editing and Preparation*

All sentences were edited using Audacity version 2.1.1 (https://www.audacityteam.org/). The audio files were processed at a sampling rate of 48 kHz and 32-bit amplitude to ensure high fidelity. The length of each sentence ranged from 3 to 4 seconds. To standardize the start times across trials, stimuli were trimmed to include approximately 150 ms of silence before the onset and 300 ms after the offset of each sentence.

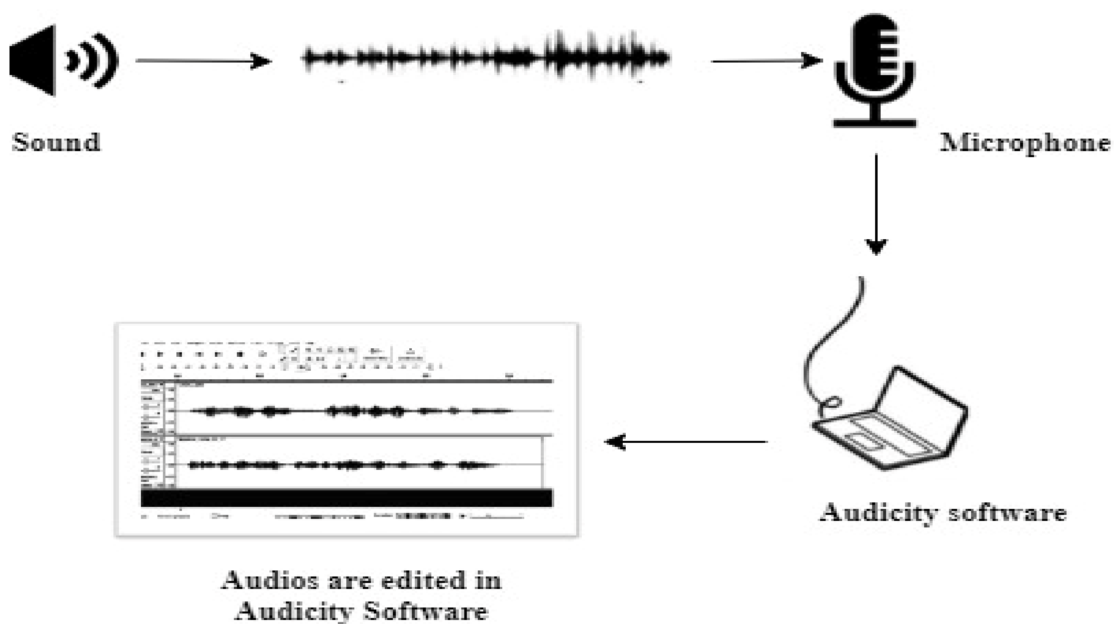


Figure 3.5: Audio Editing and Preparation

3.4.5 *Masking and Filtering*

The noise recordings were edited to ensure that two sentences were played simultaneously. The audio files were low-pass filtered at 9 kHz and high-pass filtered at 60 Hz. All masker sentences were root-mean-squared equalized to the same level as the target sentences at 25 dB, establishing a target-to-masker ratio (TMR) of zero.

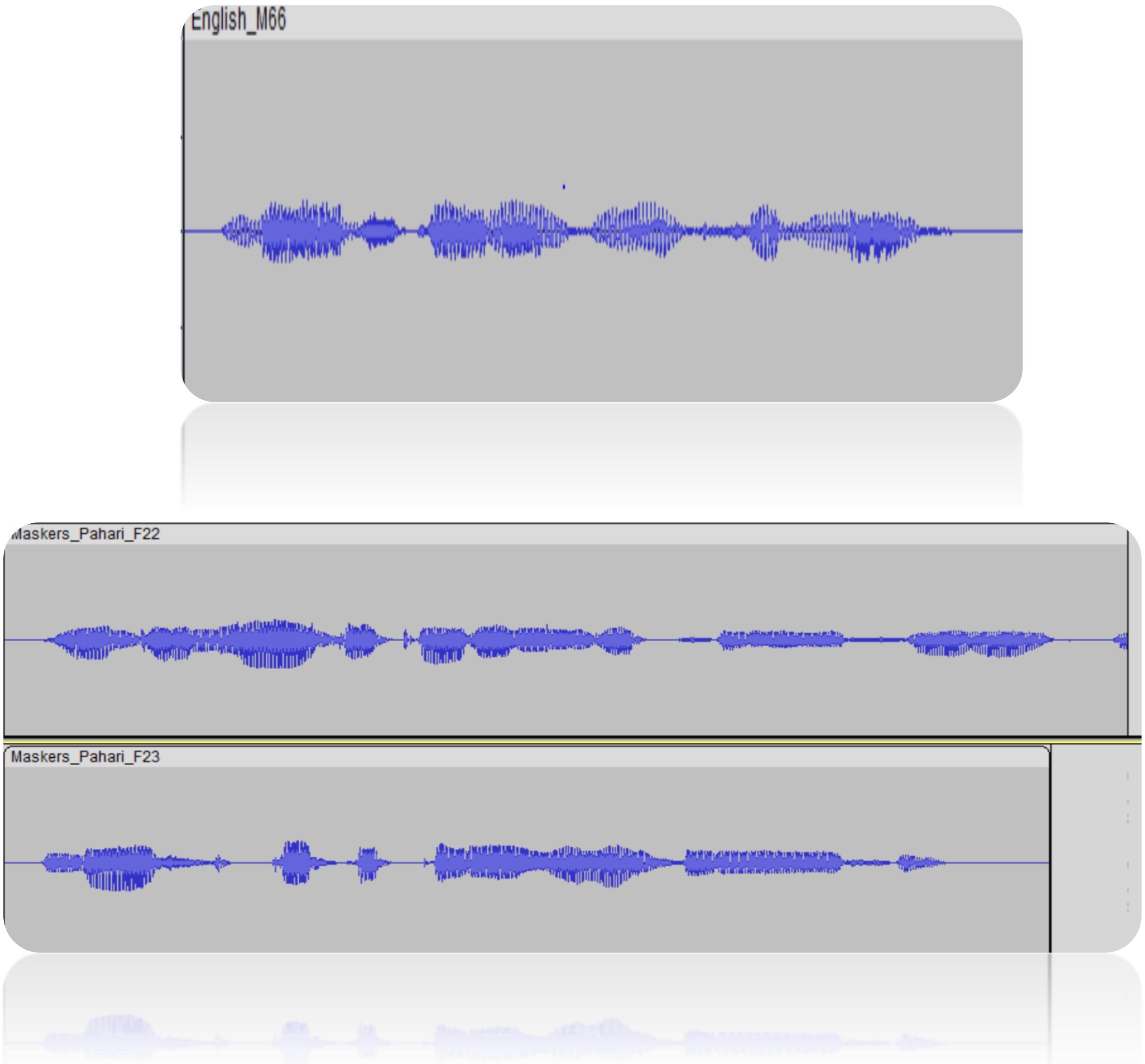


Figure 3.6: Filtering and Masking

3.4.6 Experimental Blocks and Stimuli Distribution

The study consists of three blocks, totaling 93 sentences. One block serves as a practice block and is excluded from the analysis, leaving two blocks for the main study. Each block includes target sentences amplified at 3 levels: 25 ± 2 dB, randomly distributed across trials. Each sentence consists of five key words, which are distinguished from connecting words by capitalization in English and bolding in Urdu. Pahari sentences do not utilize capitalization.

3.4.7 Audio Concatenation and keywords

Each trial involves one target sentence and two masking sentences, all played simultaneously. The final concatenated audio files include 6 minutes and 25 seconds of audio for both pre-experiment and post-experiment segments, with the practice session lasting 44 seconds.

The masking sentences are consistent in language within each trial, either both in Urdu, both in English, or both in Pahari. Participants are scored based on the number of key words they correctly identify in each target sentence.

3.5 Experimental Overview

It is a single blinded, single session design. It is employed to investigate the effect of anodal tDCS which is targeting left inferior posterior frontal gyrus IFG (pIFG) in healthy Bilingual participants to investigate that tDCS will improve auditory spatial attention in them or not. An experimental task of auditory stimulations was designed to check the tDCS effects in Prosthetics and implantology Lab SMME, NUST.

3.5.1 Participants

All participants were graduate and undergraduate university students whose native language was URDU L1 and who learnt ENLISH as L2. Out of 54 participants underwent the screening procedure and 50 (28 females, 22 males (age:24±4) right-handed participants were selected and completed the study. 4 subjects were excluded from the study.

3.5.2 *Recruitment*

Figure 3.7: Recruitment of subjects

3.5.3 *Inclusion Criteria*

Each participant was screened for any kind of medical disorders, substance abuse or dependence, use of CNS medication, psychiatric and neurological disorders (including surgery, tumor or intracranial metal implantation). All participants gave their informed consent prior to be enrolled in the study. Participants self-evaluated their Language proficiencies suing LEAP_Q 2007 questionnaire [52]to check their dominant and non-dominant language. Based on questionnaire results. Their dominant Language was URDU and non-dominant was ENGLISH. All participants had normal hearing and corrected to normal vision. All participants were Bilinguals none of them was monolinguals.

3.5.4 *Exclusion Criteria*

Exclusion criteria were concomitant medication expected to affect mental performance, current history of medication or dependence in the previous 3 months, any psychiatric disorder, recent history of stroke, head injury or seizure [53]. In according with the current study, Subjects suffering from diseases (depression, migraine, frequent headaches, Dyslexia) and those who were currently (within 3 months) on medication [54] were excluded, which can affect our study [55]. The monolinguals and participants with hearing problems, language disorders were also excluded.

3.5.5 *Ethics Statement*

The protocol was approved from the SMME Ethics Committee, NUST. Informed consent in written for was taken from all recruited subjects former to the start of study.

3.6 Experiment Session

It was a one-day experiment. The participant performed three sessions on one day. It took 35 to 40 minutes to complete the experiment.

- Practice session
- Pre tDCS /Baseline session

- Post tDCS session

Each participant filled a pre-experiment questionnaire (safety, LEAP-Q and screening forms) and after this performed a practice session of 1 to 2 minutes (one block of 5 sentences) to familiarize with the experiment. Then the pre tDCS /Baseline session began .The participant was asked to listen one block of 44 sentences (22 in URDU and 22 in ENGLISH) spoken by a male speaker and masked by female voice(background noise can be paired with either two two sentences in Urdu, English , Pahari and other combinations like English-Urdu, English-Pahari, Urdu-Pahari) .A full concatenated recording consisting of 44 sentences (Each sentence consisted of one target and two maskers) was played . The participant was asked to listen to as many sentences as she/he can listen and repeat in microphone. Their recordings were made through iPhone voice memo.

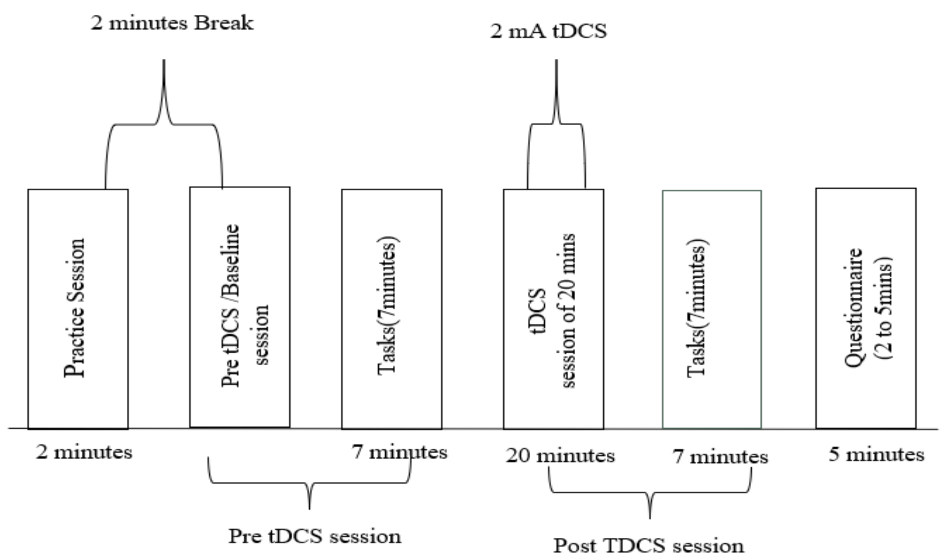


Figure 3.8: Experimental protocol

3.7 tDCS Protocol

"ActivaDose II" device was used for stimulation. Electrode size of both anode and cathode was 3x3 cm. 2 mA current was used for stimulation. The current density was 0.2 mA/cm^2. Anode electrode was placed at left posterior inferior frontal gyrus pIFG which was identified of 1/3 distance between F7 and C5 and cathode was at right shoulder. The location was measured according to 10-20 EEG system. Sponges soaked in saline water were used as conducting medium between the scalp and the electrodes. Each participant was given active tDCS.In anodal tDCS session current was ramped over 10 seconds and held constant at 2 mA for 20 minutes and then ramped down over 2-3 seconds. [56]

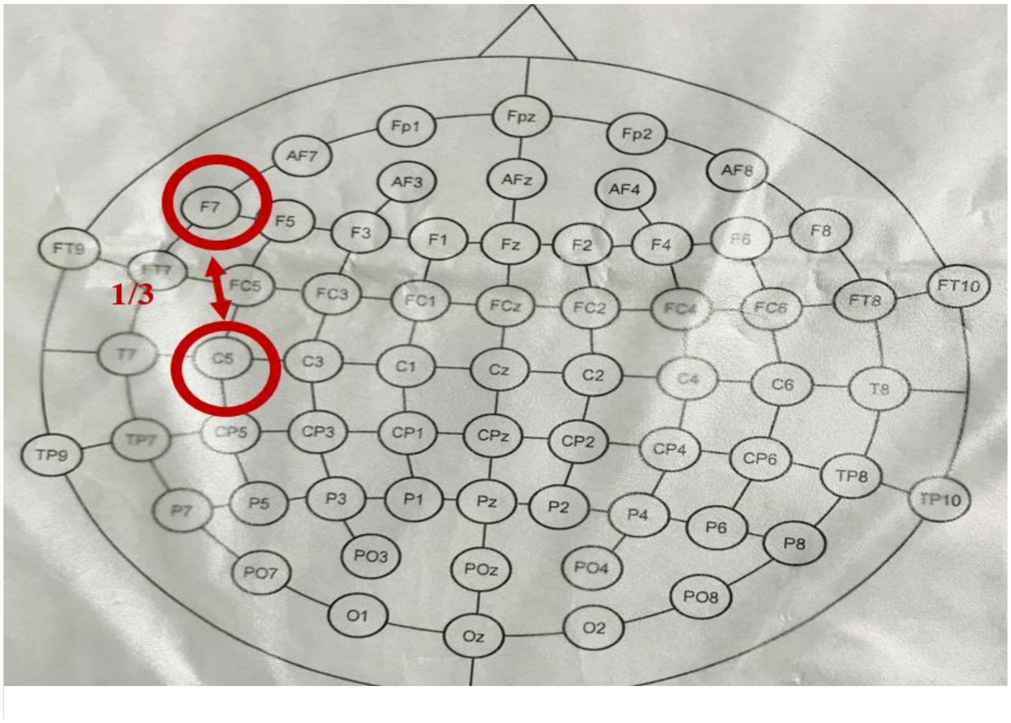


Figure 3.10: Location of pIFG

Figure 3.9: Anode is placed at left pIFG of subject

Following the practice block of 2 minutes, there will be a 2-minute break. After the break, participants were asked to listen pre tDCS block of sentences.it took 7 minutes. Then the subjects went through Active Stimulation of 2mA tDCS for 20 minutes. Following the stimulation, participants was asked to complete another one block of stimuli (consisting of 44 sentences) a task was expected to take 7 minutes. Participants repeated key words on microphone after every trial. After this, participants was be asked to fill out a tDCS adverse effects questionnaire which took 2 to 5mins. Participants were instructed not to use their cell phones or computers and to avoid interaction with the researchers unless they felt uncomfortable and wished to stop the stimulation.

Table 3.1: ActivaDose II Stimulation parameters

ActivaDose II Stimulation parameters							
Type of Stimulation	**Shape of Electrodes**	**Electrodes Insert**	**Area**	**Material**	**ent**	**Duration**	**Dose (Current x Duration)**
Active tDCS	Square	0.9 % Saline soaked sponge inserts	9 cm²	er odes	2mA	20 min ffline tDCS	40 mA min

CHAPTER 4: RESULTS

A repeated measures ANOVA is conducted on control and the experimental group's pre and post-test verbal Urdu and English scores to test the hypothesis that Active tDCS has an effect on enhancing the auditory spatial attention. This statistical analysis is for the direct comparison of the within-subject factors including scores before and after tests and the between-subject factors including the Control and the Active tDCS group for both languages to establish whether there are enhancements in the auditory spatial attention due to the Active tDCS intervention. Results are as follows.

4.1 Normality tests

To ensure the assumptions of the repeated measures ANOVA are met, a Shapiro-Wilk test is performed to check the normality of all the factors: Comparing the pre- and post-test scores of the control and Active tDCS groups in Urdu and English. The findings suggest that the p-values for all sessions are greater than 0. 05 indicating that each of the factors is normally distributed in the population. This means that the scores of pre and post tests for both languages and both groups are normally distributed as required for the application of the repeated measures ANOVA. This normality verification is important because it affirms subsequent statistical analysis. Following is the normality tests of pre and post ENGLISH, pre and post URDU of both Active and Control groups

4.2 Control vs. Active tDCS: Pre- and Post-English

The results revealed significant improvements in both the Active and Control Groups. Specifically, the Active Group demonstrated a substantial enhancement in English comprehension, evidenced by a significant F-value of 45.139 ($F(1, 48) = 45.139$, $p < 0.001$) as compared to control group which have F-value of 7.795 ($F(1,48)=7.795$,$p=0.008$).

Table 4.1: The mean, standard deviation, and sample size (N)

Group	Mean	Std.Deviation	N
Pre-English			
Active	40.20	13.077	25
Control	47.24	10.721	25
Total	43.72	12.357	50
Post-English			
Active	55.12	16.599	25
Control	53.44	11.354	25
Total	54.28	14.100	50

Table 4.2: The ANOVA results comparing pre- and post-intervention English scores for the Active and Control Groups

Group	F	df(numerator)	df(denominator)	p-value	Significance
Active Group	45.139	1	48	<0.001	Highly significant
Control Group	7.795	1	48	0.008	Significant

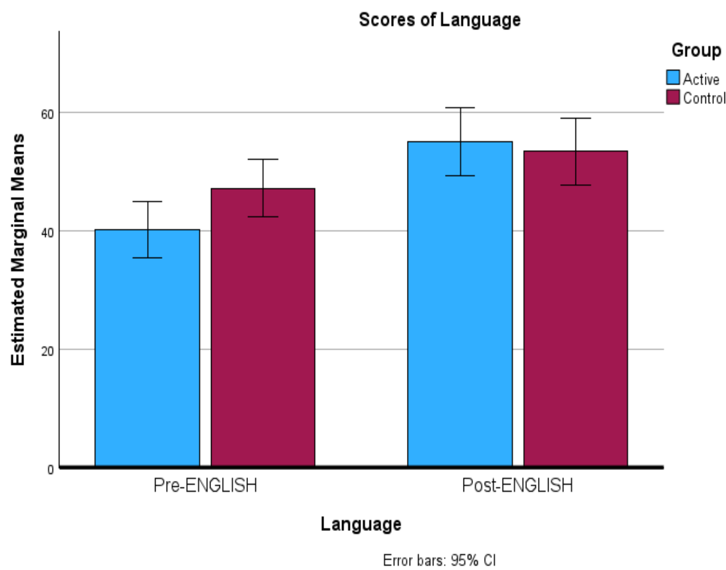


Figure 4.1: The above graph is comparing pre- and post-intervention English scores for the Active and Control Groups.

4.3 Control vs. Active tDCS: Pre- and Post-Urdu

The results revealed significant improvements in both the Active and Control Groups. Specifically, the Active Group demonstrated a substantial enhancement in Urdu comprehension, evidenced by a significant F-value of 49.088 ($F(1, 48) = 49.088$, $p < 0.001$) as compared to control group which have F-value of 8.032 ($F(1,48)=8.032$,$p=0.007$)

Table 4.3: The mean, standard deviation, and sample size (N) for pre- and post-intervention Urdu language scores for both the Active and Control Groups

Group	Mean	Std.Deviation	N
Pre-Urdu			
Active	79.44	12.833	25
Control	84.28	10.573	25
Total	81.86	11.891	50
Post-Urdu			
Active	93.68	7.537	25
Control	90.04	7.635	25
Total	91.86	7.730	50

Table 4.4: The ANOVA results comparing pre- and post-intervention Urdu scores for the Active and Control Groups

Group	F	df(numerator)	df(denominator)	p-value	Significance
Active Group	49.088	1	48	<0.001	Highly significant
Control Group	8.032	1	48	0.007	Significant

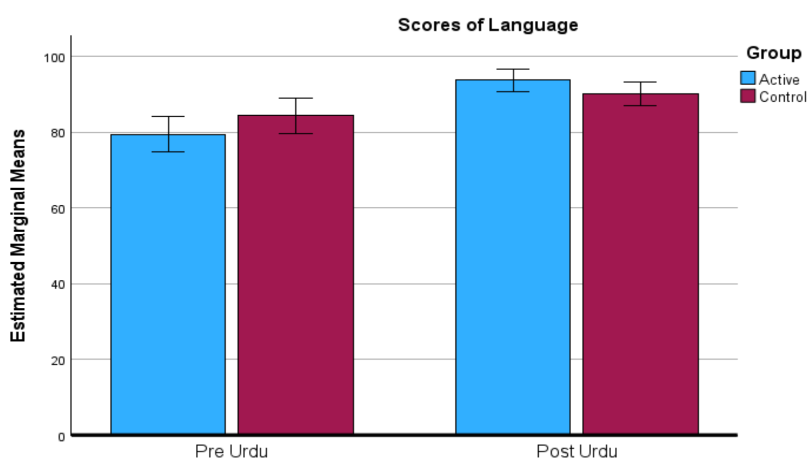


Figure 4.2: The above graph is comparing pre- and post-intervention Urdu scores for the Active and Control Groups.

4.4 Control vs. Active tDCS:pre- and post-English proficiencies

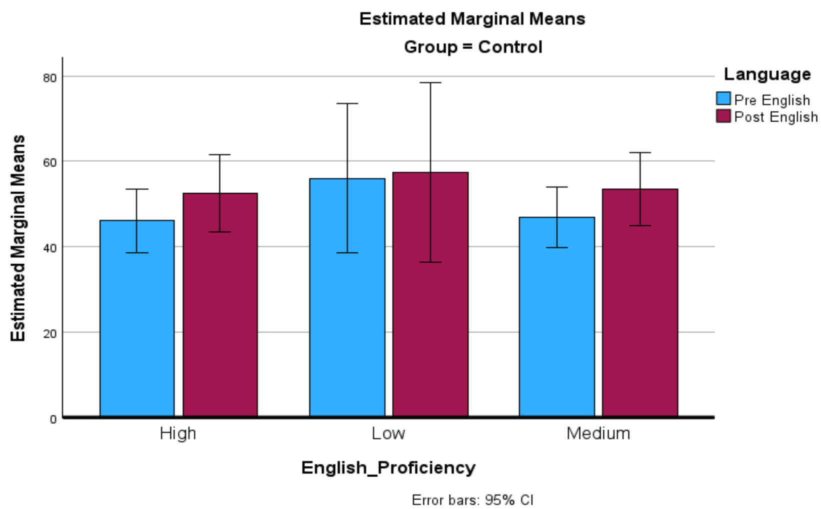
The Active Group showed a highly significant improvement with High English Proficiency ($F(1, 44) = 19.98$, $p < 0.001$ and medium English proficiency ($F(1,44)=22.9, P<0.001$), while the Control Group also demonstrated a significant improvement with High English Proficiency ($F(1, 44) = 3.569$, $p = 0.065$)and Medium English Proficiency ($F(1,44)=4.259, p=0.045$).

Table 4.5: The mean, standard deviation, and sample size (N).

Group	English Proficiency	Mean	Std. Deviation	N
Pre English				
Active	High	38.14	12.941	7
	Low	44.67	16.258	3
	Medium	40.27	13.312	15
Control	High	46.09	10.454	11
	Low	56	8.485	2
	Medium	46.83	11.376	12
Total	High	43	11.802	18
	Low	49.2	13.737	5
	Medium	43.19	12.698	27
Post English				
Active	High	57.29	17.153	7
	Low	54.33	22.279	3
	Medium	54.27	16.494	15
Control	High	52.55	8.699	11
	Low	57.5	0.707	2
	Medium	53.58	14.444	12
Total	High	54.39	12.41	18
	Low	55.6	15.852	5
	Medium	53.96	15.326	27

Table 4.6: The ANOVA results comparing pre- and post-intervention English scores for the Active and Control Groups including English proficiencies

Group	English Proficiency	F	(numerator)	(denominator)	p-value	Significance
Active	High	19.98	1	44	<0.001	Highly significant
	Low	2.184	1	44	0.147	Not significant
	Medium	22.9	1	44	<0.001	Highly significant
Control	High	3.569	1	44	0.065	Marginally significant
	Low	0.035	1	44	0.852	Not significant
	Medium	4.259	1	44	0.045	Significant



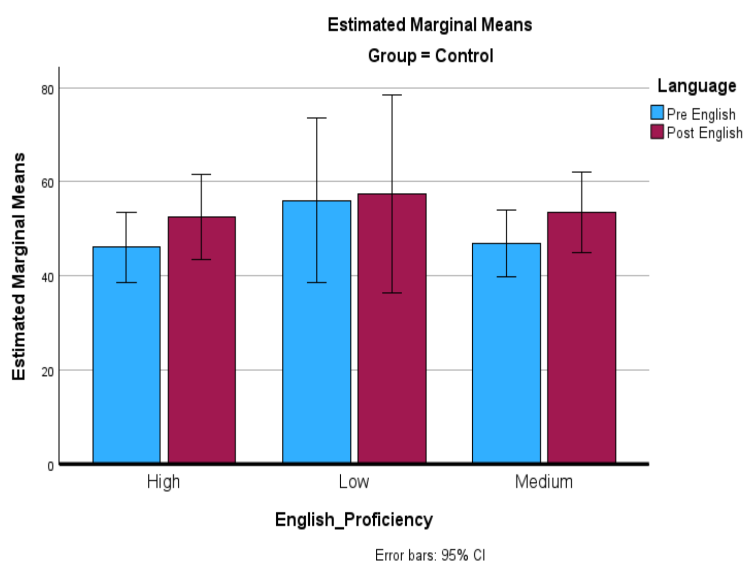


Figure 4.3: ANOVA results comparing pre- and post-intervention English scores for the Active and Control Groups including English proficiencies

4.5 Control vs. Active tDCS: Pre- and Post-Urdu with proficiencies

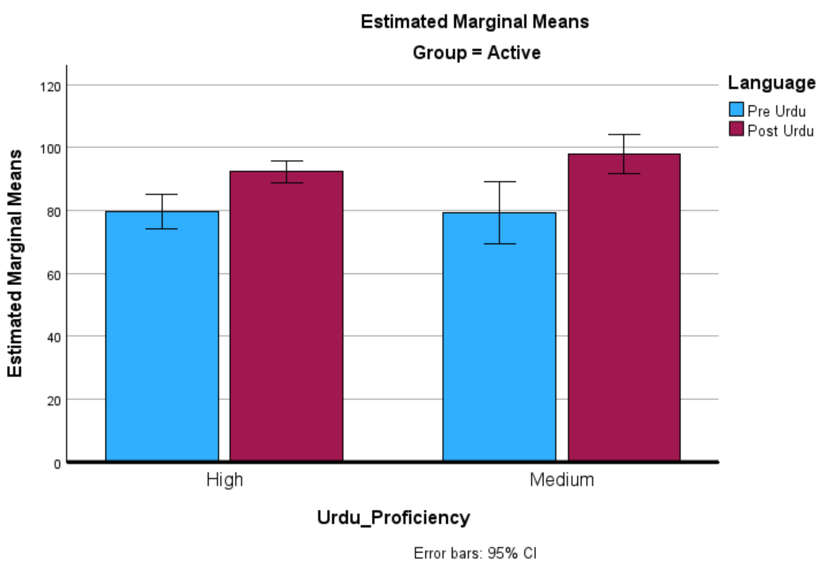
The Active Group showed a highly significant improvement with High Urdu Proficiency ($F(1, 46) = 30.221$, $p < 0.001$ and medium Urdu proficiency ($F(1,46)=20.695, P<0.001$), while the Control Group also demonstrated a significant improvement with High Urdu Proficiency ($F(1, 46) = 7.697$, $p = 0.008$)and no significance with Medium Urdu Proficiency ($F(1,46)=0.953, p=0.334$).

Table 4.7: The mean, standard deviation, and sample size (N) for pre- and post-intervention

Group	URDU Proficiency	Mean	Std. Deviation	N
Pre URDU	High	79.53	14.151	19
Active	Medium	79.17	8.329	6
	Total	79.44	12.833	25
Control	High	83.71	10.942	17
	Medium	85.50	10.351	8
	Total	84.28	10.573	25
Total	High	81.50	12.736	36
	Medium	82.79	9.744	14
	Total	81.86	11.891	50
Post URDU	High	92.32	8.063	19
Active	Medium	98.00	3.033	6
	Total	93.68	7.537	25
Control	High	90.53	6.084	17
	Medium	89.00	10.650	8
	Total	90.04	7.635	25
Total	High	91.47	7.153	36
	Medium	92.86	9.272	14
	Total	91.86	7.730	50

Table 4.8: The ANOVA results comparing pre- and post-intervention Urdu scores for the Active and Control Groups**.**

Group	English Proficiency	F	(numerator)	(denominator)	p-value	Significance
Active	High	30.221	1	46	<0.001	Highly significant
	Medium	20.695	1	46	<0.001	Highly significant
Control	High	7.697	1	46	0.008	Marginally significant
	Medium	0.953	1	46	0.334	Not Significant



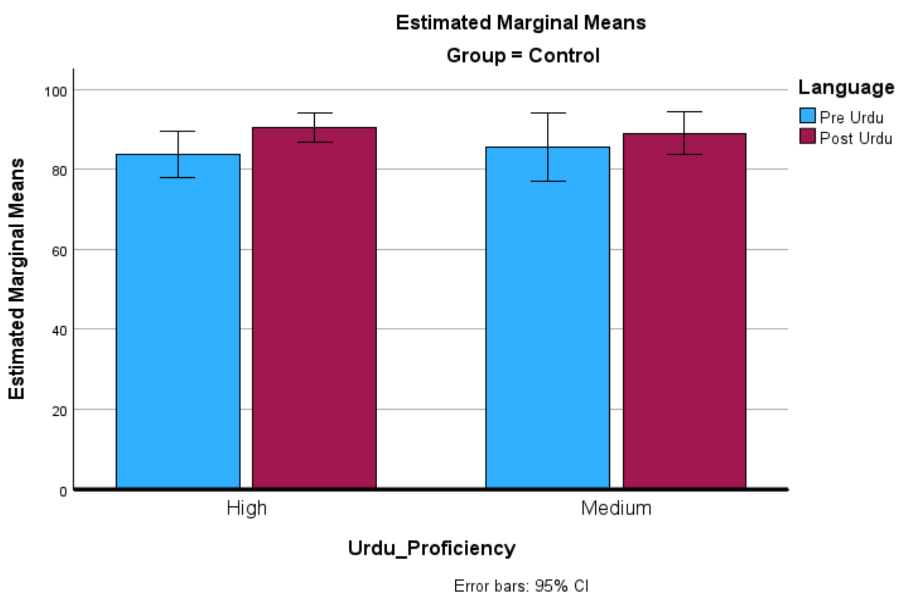


Figure 4.4: The ANOVA results comparing pre- and post-intervention Urdu scores for the Active and Control Groups. The Active Group

CHAPTER 5: DISCUSSION

The present study explored the effects of anodal transcranial Direct Current Stimulation (tDCS) on language comprehension in bilingual individuals, revealing significant improvements in both native language (Urdu) and second language (English) comprehension. For the Active Group, the analysis of variance (ANOVA) results demonstrated a highly significant improvement in English comprehension ($F(1, 48) = 45.139$, $p < 0.001$) and Urdu comprehension ($F(1, 48) = 49.088$, $p < 0.001$). These findings suggest that the tDCS intervention had a robust impact on cognitive functions related to language processing, significantly enhancing proficiency in both languages. The Control Group also showed significant improvements, though less pronounced, with an F-value of 7.795 and $p = 0.008$ for English, and an F-value of 8.032 and $p = 0.007$ for Urdu, indicating that practice or exposure alone also contributed to some gains. Further analysis within the Active Group revealed substantial improvements across different proficiency levels. Participants with high English proficiency showed significant gains ($F(1, 44) = 19.98$, $p < 0.001$), as did those with medium proficiency ($F(1, 44) = 22.9$, $p < 0.001$). Similarly, for Urdu comprehension, high proficiency participants had an F-value of 30.221 and $p < 0.001$, while medium proficiency participants had an F-value of 20.695 and $p < 0.001$. These results indicate that tDCS can effectively enhance language comprehension across various proficiency levels.

In contrast, the Control Group displayed less pronounced improvements, with high English proficiency participants showing an F-value of 3.569 and $p = 0.065$, and medium proficiency participants an F-value of 4.259 and $p = 0.045$. For Urdu comprehension, high proficiency participants had an F-value of 7.697 and $p = 0.008$ showed significant results, while medium proficiency participants had an F-value of 0.953 and $p = 0.334$ and showed no significant results. These findings suggest that while the Control Group did benefit from practice or exposure, the effects were not as substantial as those observed in the Active Group.

The results align with previous research suggesting that tDCS can improve cognitive functions such as learning, memory, and language processing. Anodal tDCS, in particular, increases cortical excitability and promotes neuroplasticity, making it a promising tool for enhancing comprehension skills. The study's findings are consistent with the notion that the brain regions associated with language comprehension—such as the left inferior frontal gyrus (LIFG) and posterior superior temporal gyrus (STG)—can be modulated by tDCS. This is especially relevant for bilingual individuals, who rely on these regions to manage and switch between two languages. The stimulation likely enhances the excitability of neurons in these areas, allowing for more efficient language processing.

One of the key contributions of this study is the demonstration that tDCS can improve comprehension in both the native and second languages. Prior research has suggested that second language (L2) processing is more cognitively demanding than first language (L1) processing, as L2 proficiency tends to be lower and may require more effort. However, the improvements observed in this study suggest that tDCS enhances comprehension in both languages, potentially by facilitating neural processes that support language comprehension, such as working memory and attentional control. These findings indicate that tDCS could serve as a cognitive enhancer for bilinguals, improving their ability to comprehend languages regardless of proficiency level.

The consistency of tDCS effects across different proficiency levels is another noteworthy aspect of this study. Participants with high proficiency in English showed significant improvements, as did those with medium proficiency, demonstrating that tDCS can benefit individuals at various stages of language proficiency. For high-proficiency participants, tDCS may enhance the efficiency of already well-established neural pathways involved in language processing, leading to more rapid and accurate comprehension. For medium-proficiency participants, the stimulation may support the development of neural connections that are still being reinforced, accelerating their language acquisition and comprehension skills. These results suggest that tDCS may offer a cognitive advantage for bilingual learners, enabling them to improve comprehension regardless of their initial proficiency in the language.

The modest improvements observed in the Control Group reflect the role of practice effects in language comprehension tasks. Participants in the Control Group, who did not receive active stimulation, still showed some gains, particularly in high-proficiency English speakers. This suggests that practice and repeated exposure to language tasks can lead to improvement over time, although the gains were less pronounced than those seen in the Active Group. The Control Group's performance may also reflect the cognitive advantages associated with bilingualism, as bilingual individuals often display enhanced executive control when managing two languages. However, the fact that the improvements were significantly greater in the Active Group underscores the potential of tDCS as a tool for enhancing language comprehension beyond the effects of practice alone.

The findings of this study hold significant implications for educational and clinical applications. In educational settings, tDCS could be integrated into language learning programs to support bilingual education. Bilingual learners often face challenges related to managing cognitive load and switching between languages, which can affect their ability to comprehend and learn effectively in both languages. By enhancing language comprehension in both L1 and L2, tDCS could help mitigate these challenges, potentially leading to faster and more efficient language acquisition. This could be particularly beneficial in academic settings, where bilingual students are often required to process information in both their native and second languages.

In clinical contexts, tDCS could be used as a therapeutic intervention for individuals with language impairments, such as those recovering from stroke or traumatic brain injury. For bilingual individuals with aphasia, for example, tDCS could be applied to facilitate recovery of language comprehension in both their native and second languages. The significant improvements observed in this study suggest that tDCS may promote neuroplasticity and support language rehabilitation in clinical populations. Additionally, the ability of tDCS to enhance comprehension in individuals with different proficiency levels indicates that it could be applied to a wide range of clinical cases, from those with mild impairments to those with more severe language deficits.

5.1 Limitations

The limitations of this study are significant and need to be carefully considered when interpreting the results. One of the primary limitations is that the study exclusively focused on Urdu-dominant bilinguals, which restricts the generalizability of the findings to bilinguals of different language backgrounds. Language processing can vary depending on the specific languages spoken, and the cognitive demands of switching between languages with different linguistic structures may result in varied effects from tDCS. Thus, the improvements observed in Urdu and English bilinguals may not apply to speakers of other languages.

Additionally, the intervention was more effective for high- and medium-proficiency participants, while low-proficiency bilinguals did not experience significant improvements. This suggests that tDCS may be more beneficial for individuals who already have established language networks, and it may not be as effective for those still developing proficiency in their second language. This raises questions about the scalability of the intervention across varying proficiency levels and its potential limitations for lower-proficiency learners.

Another limitation involves the relatively small sample size, particularly within the medium-proficiency group, which may affect the reliability of the results. Small sample sizes increase the risk of variability and can limit the statistical power of the study. Moreover, the study only included a single session of tDCS, making it unclear whether the observed improvements would be sustained over time or with repeated sessions. Future research should investigate the effects of multiple tDCS sessions to determine whether more prolonged or repeated interventions would result in greater or more lasting improvements in language comprehension.

Finally, the study focused on stimulating a single brain area, potentially oversimplifying the complex neural networks involved in language processing. Language comprehension involves multiple regions of the brain, and targeting only one area may have overlooked other critical regions that contribute to bilingual language proficiency. Future studies should consider a more comprehensive approach by examining the broader neural mechanisms at play in language learning and comprehension.

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CHAPTER 6: CONCLUSION AND FUTURE RECOMMENDATIONS

6.1 Conclusion

In conclusion, this study shows that anodal tDCS over the left pIFG improves auditory comprehension in both native and non-native languages, with greater impact on the dominant language, especially among those with higher proficiency levels. These findings suggest pathways for further investigation of tDCS in language learning and rehabilitation, particularly in multilingual environments.

6.2 Future Recommendation

To make the study's results more reliable, future research should include bilinguals who speak languages other than Urdu. This would help us understand how language learning works for different people. It would also be helpful to have more sessions in the study and to look at more parts of the brain.

In the future, researchers should focus on helping bilinguals who aren't very good at speaking both languages. This way, we can find better ways to help everyone learn languages well, no matter their starting level. These changes would make our research more useful for teachers and learners everywhere.

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