INVESTIGATING THE BRAIN ENERGY DYNAMICS DURING LANGUAGE ACTIVITY

by

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ACADEMIC ETHICS AND INTEGRITY STATEMENT

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ABSTRACT

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The present dissertation aimed to measure the overall cognitive cost of language and visual processing to the brain with ear temperature measurement. Three verbal auditory experiments revealed that processing words caused a greater temperature increase in the left ear than the right ear, indicating an expected left-hemispheric activity for language processing. Furthermore, processing words from a non-native language (English) caused greater cognitive cost (greater temperature increase) compared to words from the native language (Turkish). Lastly, it was found that the greatest temperature increase was caused by the most difficult task. The last auditory experiment assessed the frontal cortex hemodynamics with functional near-infrared spectroscopy (fNIRS) and showed that the left hemisphere was active throughout the experiment, while the most difficult task caused the most widespread neuronal activity. A visual discrimination task revealed a greater temperature increase in the right ear compared to the left ear. These findings suggested that ear temperature can capture the overall cognitive cost of lateralized brain functions and can dissociate the task difficulty. A novel mental rotation (MR) and Turkish relative clause (RC) processing experiments were carried out with fNIRS to further investigate the cognitive cost of visual and language processing as well as to assess the hemisphere's contributions to processing. The MR experiment revealed a core neuronal activity in the right hemisphere regardless of the task difficulty and increased left-hemispheric activity with increased task difficulty. RC processing in Turkish was investigated with a neuroimaging method for the first time and it was shown that processing object RCs causes greater cognitive load than subject RCs, reflected by more widespread neuronal activity in the prefrontal cortex and greater non-significant hemodynamic activity in Broca's Area.

Keywords: Tympanic Membrane Temperature, fNIRS, Language Processing, Visual Processing, Cognitive Cost.

ÖZET

DİL İŞLEME SIRASINDA BEYİN ENERJİ DİNAMİKLERİNİN İNCELENMESİ

Bu tezde, dil ve görsel işlemenin beyinde yarattığı bilişsel yükün kulak sıcaklığı ile ölçülmesi amaçlanmıştır. Üç adet işitsel kelime deneyi, kelime işlemenin sağ kulağa kıyasla sol kulakta daha fazla sıcaklık artışına neden olduğunu göstermiştir. Bu da genel olarak dil işlemenin gerçekleştiği varsayılan sol hemisfer etkinliğini yansıtmaktadır. Ayrıca, kişinin anadilinden olmayan (İngilizce) kelimelerin işlenmesinin, anadilindeki (Türkçe) kelimelere kıyasla daha fazla bilişsel yüke neden olduğu ve en zor deney görevinin en yüksek kulak sıcaklık artışına neden olduğu bulunmuştur. Son işitsel kelime deneyinde frontal korteksin hemodinamik etkinlikleri işlevsel yakın-kızılötesi spektroskopisiyle (iYKAS) incelendi ve sol hemisferin deney boyunca aktif olduğu, en zor deney görevinin prefrontal kortekste en yaygın nöronal etkinliğe neden olduğu bulundu. Görsel işleme deneyi, sıcaklık artışının sol kulağa kıyasla sağ kulakta daha fazla olduğunu gösterdi. Bu bulgular, kulak sıcaklığı ölçümünün lateralize beyin işlevlerinin genel bilişsel yükünü ölçebileceğini ve deney zorluklarını ayırt edebileceğini gösterdi. Görsel ve dil işlemeyi bilişsel yük açısından farklı düzeyde incelemek ve hemisferlerin bu bilişsel işlevlere olan katkılarını değerlendirmek için iYKAS ile mental döndürme (MD) ve Türkçede ilgi tümleçlerinin işlenmesi deneyleri yapıldı. Görev zorluğundan bağımsız olarak MD deneyinin sağ hemisferde nöral etkinliğe neden olduğunu ve görev zorluğu arttıkça sok hemisferdeki etkinliğin de arttığını ortaya çıkardı. Türkçedeki ilgi tümleçlerinin işlenmesi ilk kez nörogörüntüleme yöntemiyle araştırıldı ve nesne niteleyen ilgi tümleçlerinin özne niteleyen ilgi tümleçlerinin kıyasla daha fazla bilişsel yüke neden olduğu bulundu. Nesne niteleyen ilgi tümleçlerinin işlenmesinin hem prefrontal kortekste daha yaygın nöronal aktiviteye hem de özellikle Broca Alanında daha yüksek hemodinamik aktiviteye neden olduğu bulunmuştur.

Anahtar Sözcükler: Timpanik membran sıcaklığı, işlevsel yakın kızılaltı spektroskopisi, dil işleme, görsel işleme, blişsel yük.

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$T_{left,base}$	Temperature of the left ear at the beginning of the experiment.
$T_{right,base}$	Temperature of the right ear at the beginning of the experiment.
T_{base}	Temperature difference between ears at the beginning of the experiment.
$T_{left,last}$	Temperature of the left ear at the end of the experiment.
$T_{right,last}$	Temperature of the right ear at the end of the experiment.
T_{left}	Temperature difference of the left ear from beginning to the experiment.
T_{right}	Temperature difference of the right ear from beginning to the end of the experiment.
T_{diff}	Temperature difference between ears from beginning to the end of the experiment.
$Mean_{act}$	Average HBO concentration of post-stimulus activity period.
$Mean_{base}$	Average HBO concentration of pre-stimulus baseline period.
Std_{base}	Standard deviation of HBO concentration of pre-stimulus baseline period.
$HL_{sub,con}$	Hemispheric lateralization of each subject for each condition.
N_{LC}	Number of active fNIRS channels in the left hemisphere.
N_{RC}	Number of active fNIRS channels in the right hemisphere.
N_C	Number of total fNIRS channels in a hemisphere.
Max_{act}	Maximum HBO concentration of post-stimulus activity period.
$T_{thermistor}$	Sensor (i.e., ambient) temperature in Kelvin degrees.
p_{1-4}	Polynomial coefficients.
X	ADC output value for thermistor signal.
V_{obj}	Voltage generated by thermopile.
K	Thermopile sensor constant.
T_{obj}	The temperature of the target object in Kelvin degrees.
T_{amb}	The ambient (i.e., sensor) temperature in Kelvin degrees.

ϵ	Emissivity of the target object.

LIST OF ABBREVIATIONS

ADC	Analog-to-Digital Converter
ANOVA	Analysis of Variance
ATP	Adenosine Tri-Phosphate
BA	Brodmann Area
cm	centimeter
DLPFC	Dorsolateral Prefrontal Cortex
DMTS	Delayed match-to-sample
fNIRS	functional Near-Infrared Spectroscopy
HAS	Hemodynamic Activity Strength
HBO	Oxyhemoglobin
HBR	Deoxyhemoglobin
HBT	Total Oxyhemoglobin
HDMI	High-Definition Multimedia Interface
HL	Hemispheric Lateralization
Hz	Hertz
ILHG	Interlingual Homograph
ILHP	Interlingual Homophone
ISI	Inter-Stimulus Interval
kHz	kiloHertz
kOhm	kiloOhm
LED	Light Emitting Diode
MHz	Mega Hertz
μF	microFarad
μA	micro Ampere
mm	millimeter
MR	Mental Rotation
ms	milliseconds
NIRS	Near-Infrared Spectroscopy

nm	nanometer
NTC	Negative Temperature Coefficient
ORC	Object Relative Clause
O_2	Oxygen
PTC	Positive Temperature Coefficient
RT	Reaction Time
RTD	Resistance Temperature Detector
SRC	Subject Relative Clause
TMT	Tympanic Membrane Temperature
uH	micro Henry

1. INTRODUCTION

1.1 Motivation and Background

Humans can perform multiple tasks simultaneously. Our brains have been evolved to process massive amounts of information coming from different modalities (e.g., visual, auditory, olfactory, etc.) for performing various cognitive and motor tasks simultaneously to survive and successfully navigate the world. On the other hand, our brains have a limited information processing capacity [4]. Therefore, it is inevitable that the brain must allocate its resources ’wisely’ to sustain its activities without vital failures. It is also reasonable that the resource allocation or distribution process depends on the importance of the ongoing cognitive activities at a time. Performing any task more efficiently with fewer resources is an advantage and would be an ultimate goal for any system, including the brain. It can be speculated that if the brain uses less neuronal resources to perform some cognitive activities, then the remaining available resources can be allocated for the others, leading to increased overall performance. Unsurprisingly, language is one of the simultaneously used cognitive faculties as we use it to communicate and to cooperate with our peers in various contexts. On the other hand, people speak different languages and it is very unlikely that the different languages have the same cognitive cost to our brains.

It is a well-known fact that language processing occurs mainly in the left hemisphere for most humans [5, 6]. On the other hand, it is thought that there are approximately 6000-7000 languages in the world [7, 8]. We know that languages vary in their features such as grammar, syntax, phonetics, lexicon size, etc. possibly due to the different historical backgrounds and evolutions over time. In other words, it can be speculated that people speaking different languages have roughly the same hardware (i.e., neuronal resources) and different software (i.e., languages) to perform similar linguistic functions. Moreover, the functionality of different languages seems to similar despite these differences. However, it is very likely that these different features can also cause processing differences among languages, which would be reflected in the employed strategies, neuronal activation, and allocated neuronal resources. Therefore, it can be claimed that the cognitive load of different languages varies. Comparing languages in terms of their cognitive loads can reveal the possible cognitive burden for the native speaker of different languages.

Hence, the main aim of the present study was to investigate and compare the cognitive load or energy dynamics of different languages at the word processing level. More specifically, I compared auditorily processing of Turkish monolingual words and Turkish/English interlingual words by employing tympanic membrane temperature (TMT) and functional near-infrared spectroscopy (fNIRS) methods. With these experiments, I aimed to reveal the cognitive load and energy dynamics of processing a word from two different languages. It is known that fNIRS dissociate the left-right hemispheric lateralization and reflect task-difficulty related neuronal activity changes in many experiments. However, TMT has not been used widely for the same purposes. Thus, the secondary aim of the present dissertation was to show that simple, non-invasive TMT measurement is a reliable method to assess the hemispheric lateralization and to dissociate the magnitude of the neuronal activity in various cognitive tasks with varying levels of difficulty. To that end, I carried out a visual processing experiment (i.e., simple visual discrimination task) known to induce neuronal activation in the right hemisphere, in addition to the auditory language processing experiments. I also developed novel visual processing (i.e., mental rotation) and sentence processing (i.e., relative clause) experiments with the fNIRS method to dissociate the distinct contributions of the left and right hemispheres to visual processing and language processing tasks. The mental rotation experiment included three difficulty levels, allowing to assessment the effect of task difficulty on neuronal activity in both hemispheres. On the other hand, the relative clause experiment was designed to assess language processing at the sentence level. The other motivation for carrying out these experiments with the fNIRS method was to establish a base for future TMT experiments. The last aim of the present thesis was to develop a new ear thermometer to be used in future studies so that a more precise analysis can be performed. The new thermometer was aimed to be superior to the commercial thermometers in terms of accuracy, sampling rate, and resolution.

The experiments carried out in the present thesis used different paradigms, thus the pertinent literature is provided in each section in detail. In the following sections, the methods used in the present thesis is explained.

1.2 Method Overview

1.2.1 Neural Activation and Temperature

Information processing mainly occurs in the human brain and requires a steady and considerable amount of energy. Laughlin et al. [9] have shown that transmitting a single bit of information via a chemical synapse costs 10^4 ATP, while it costs 10^6 to 10^7 ATP for spike coding. Therefore, even though the brain approximately weighs 2% of the total body weight [10], it consumes approximately 20% of the O_2 and glucose utilized in the body [11] to meet the high energy demands even during a resting state. In the case of an evoked neuronal activation, the brain needs more energy (i.e. ATP), resulting in greater oxygen and glucose supply to the active brain region. Oxygen and glucose are consumed in cellular respiration to produce ATP, and heat is one of the byproducts of this metabolic process. Hence, increased neuronal activation is expected to cause a temperature increase in the active brain region locally.

Thermoregulation of the brain is crucial for various reasons. Kiyatkin (2010) has claimed that hyperthermia can increase the permeability of the blood-brain barrier, thus causing irreversible damage to the brain tissue [12]. On the other hand, various studies have produced contradictory results about the positive [13, 14] or negative [15] effects of hyperthermia on cognitive performance. All in all, it could be concluded that the thermal homeostasis of the brain is crucial in terms of health and normal functioning. Mrozek et al. (2012) have claimed that three factors affect the brain temperature: local heat production, the temperature of arteries and veins, and the cerebral blood flow that removes the local heat [11]. It is known that brain temperature, in general, is higher than the temperature of the incoming arterial blood [16,17]. Therefore, it might be expected that the local brain temperature will decrease upon activation, due to the increased cooler blood flow towards the activated warmer region. However, Sukstankii and Yablonskiy (2006) have created a more elaborative theoretical model of temperature changes in the brain and found that the temperature of the superficial brain surfaces is lower than the deep brain regions due to the heat dissipation through the skull [18]. Hence, incoming arterial blood will likely warm up the superficial cortex surfaces. They also stated that if the blood flow and the O_2 consumption is proportional then there might be no temperature change at all in the brain. Thus, the relationship between the temperature variation of the brain and neuronal activation is complex and has not yet been fully explored.

Numerous studies have reported lateralization in the brain to some extent for some cognitive abilities such as left hemispheric dominance for language processing [19, 20] and right hemispheric dominance for visuospatial processing [19, 21]. It was also shown that the brain temperature reflects the ongoing neuronal activity [22, 23]. Thus, lateralization in the brain temperature would also be expected. Indeed, various studies have shown that brain temperature also undergoes symmetrical changes upon lateralized tasks [24–27].

Different methods have been proposed for measuring brain temperature. Deep brain or cortical temperature recordings provide the most reliable results, but require craniotomy and can only be used during neurosurgeries [28]. Rectal [29] and esophageal [30] measurements are also used for monitoring the brain temperature. Although these methods reflect the brain temperature realistically, their invasiveness makes them less preferable, especially for research purposes. Thermoencephaloscopy is a non-invasive technique used by Shevelev (1992) to monitor brain temperature [31]. However, this method requires expensive apparatus such as an infrared camera, scanner system, and complex signal processing. Probing ear, or more precisely, the tympanic membrane temperature was found to be very useful to measure the brain temperature.

Ear Temperature.

Tympanic membrane temperature measurement was developed by Benzinger in the 1960s to investigate the thermoregulation of the human body [32]. Various studies have been carried out with tympanic membrane temperature measurements since then [25, 33–36]. Ear temperature measurements allow monitoring of the brain temperature based on two phenomena. First, the ear and eardrum are anatomically close to the brain, thus they reflect the temperature of the resting brain due to dissipated heat from neuronal tissue [37]. Secondly, the brain and the ear (more specifically tympanic membrane and cavity) share a common arterial system. It is the carotid arteries that supply the middle ear and ipsilateral hemisphere. The carotid artery supplies the head, face, and neck with two main branches: the internal carotid artery and external carotid artery [38]. The external carotid artery mainly supplies blood to the neck and face, while the internal carotid artery supplies blood to the brain via cerebral arteries. Although the middle ear and the tympanic membrane are supplied by both internal and external carotid arteries, the temperature of the tympanic membrane and middle ear is affected predominantly by the internal carotid artery due to anatomical proximity (Figure 1.1). Therefore, increased oxygen and glucose demands of the brain are met by the increased blood supply partly via internal carotid arteries. This allows monitoring the fluctuations of the brain temperature, which is caused by the altered circulation, from the ear canal (i.e. tympanic membrane). To sum up, studies have shown that the ears also reflect the temperature changes in their ipsilateral cortices [39, 40].

Helton (2010) has claimed that tympanic membrane temperature dynamics can be assessed with between-subjects design or within-subjects design [41]. The between-subjects assessment provides information about the different states (i.e. moods or activity levels) of the brain, while the within-subjects assessment explains the neuronal response of the brain to a temporal stimulation (i.e. resting vs. stimulation). Various between-subjects design studies have shown that the warmer hemisphere is more active or has greater overall resting activation than the cooler hemisphere [27, 41]. Furthermore, Genovese et al. (2017) also showed that the warmer hemisphere is the dominantly active one in resting [42]. Therefore, it can be claimed that the warmer hemisphere

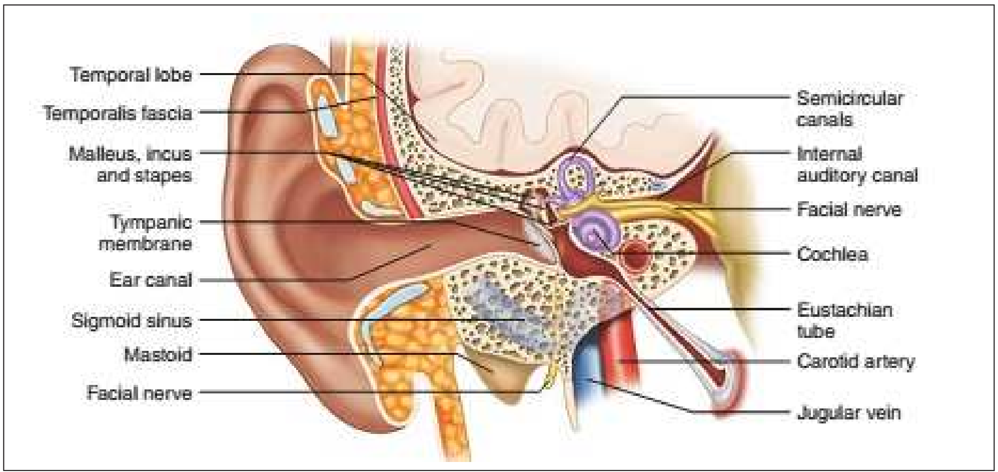

Figure 1.1 Ear anatomy [1].

shows greater activity at rest. On the other hand, within-subject level studies have produced contradictory results. It is a well-established fact that the core temperature of the brain is higher than of the incoming arterial blood [16,25,41]. Some studies have claimed that the increased hemispheric activity is followed by the decreased temperature in the ipsilateral ear due to the cooling effect of the arterial blood [25, 33, 37]. Cherbuin and Brinkman (2007) have shown that the word rhyming task, which is thought to be regulated dominantly by the left hemisphere, caused a greater decrease in left TMT than right TMT, while a mental-cube folding task produced the opposite result [25]. On the other hand, Swift (1991) has found a positive relationship between the increased activity of a left hemisphere and the ipsilateral ear temperature during a word recognition task [35]. Moreover, Parr and Hopkins (2000) reported increased right TMT of chimpanzees after watching a negative emotional video [24]. The authors have explained that the right hemisphere is responsible for processing negative emotions according to the valence theory of emotions. Thus, their findings can also be considered as favoring the increased hemispheric activity and the increased ipsilateral TMT theory.

Another study has shed further light on the complex dynamics of ear temperature. Lorr et al. (2017) has investigated the relationship between the tympanic membrane temperature and middle cerebral artery flow during a head-up tilt study [43]. In this study, the subjects were moved from supine position to 50° head-up position via a tilt table. The authors found that decreased mean cerebral blood flow is accompanied by a decrease in tympanic membrane temperature. Furthermore, the authors have claimed that the internal jugular vein can also affect TMT. Deoxygenated blood in the brain flows towards to heart via jugular vein, which is anatomically close to the tympanic membrane (Figure 1.1). Therefore, relatively warmer blood coming from the brain can increase the temperature of the tympanic membrane. The authors have also stated that the temperature dynamics of the ear canal are different from that of the tympanic membrane because they are supplied by distinct arterial networks. They have stated that the warmer ear canal can affect the TMT measurements. Therefore, TMT results should be interpreted carefully by taking into account the measurement method and system.

1.2.2 Neural Activation and Near-Infrared Spectroscopy

Functional near-infrared spectroscopy is a relatively novel method for non-invasive imaging of the brain [44]. The method relies on the ongoing neurovascular coupling of the brain. Active neurons require more energy which is generated by utilizing glucose and oxygen in cellular respiration. Therefore, increased activation of a specific brain region causes a cascade of events: locally increased amount of oxygen consumption; decrease in the local concentration of oxyhemoglobin (HBO) and increase in the local concentration of deoxyhemoglobin (HBR); increase in blood supply (i.e. flow) towards to activated region to meet the increased needs for glucose and oxygen [45]. The blood flow towards the active region exceeds the needs of that specific region, causing an increase in the HBO concentration and a decrease in the HBR concentration. Thus, changes in hemoglobin concentrations indirectly reflect the ongoing activity of the brain.

Within the 700-900 nm spectrum, oxyhemoglobin and deoxyhemoglobin have relatively higher light absorption than water (Figure 1.2). Therefore, it allows measuring and monitoring the changes in HBO and HBR, thus the hemodynamic activity of the brain. As can be seen in Figure 1.2, the absorption factors of these chromophores

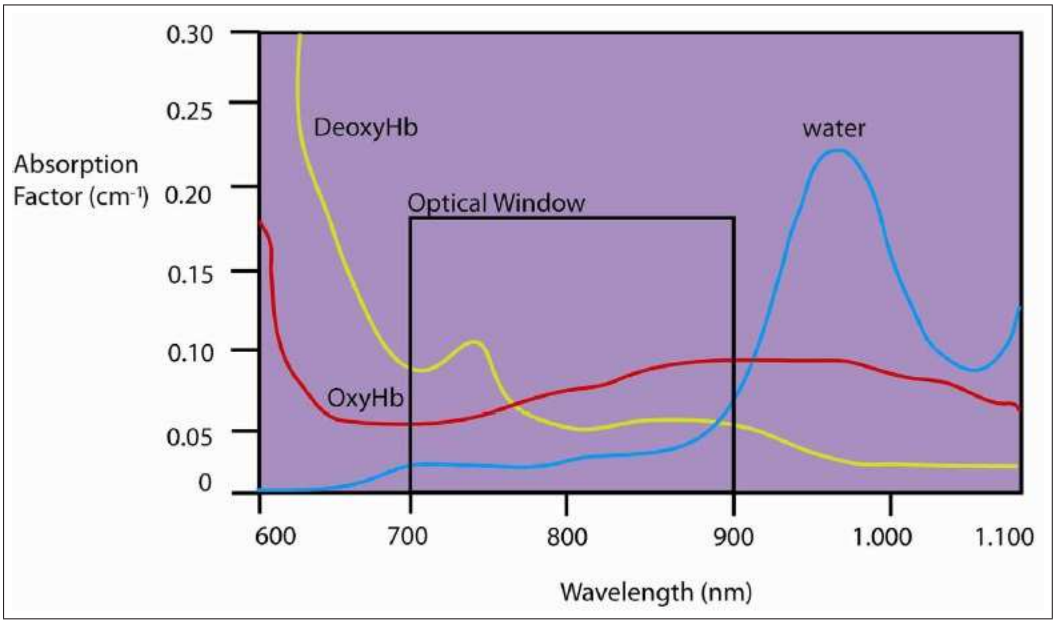

Figure 1.2 Light absorption factors of oxyhemoglobin, deoxyhemoglobin, and water [2].

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change with the wavelength. HBO and HBR concentrations are calculated by performing NIRS recordings with two different wavelengths. To do so, light-emitting diodes (LEDs) are used to emit light at predefined wavelengths, while the photodetectors are used to capture the attenuated light by the chromophores (Figure 1.3). fNIRS can penetrate approximately the top 2 cm layer of the cortex and collect signals from these regions [3, 46]. The sum of the HBO and HBR changes provides the change in total oxyhemoglobin concentration, which reflects the cerebral blood volume (or flow) change locally.

The number of fNIRS studies has been increasing dramatically especially in the last two decades. Some groups have investigated brain diseases with fNIRS such as schizophrenia [47, 48], migraine [49], while others have used fNIRS in brain-computer interface studies [21, 50, 51]. There are also studies in which the fNIRS is used during cognitive tasks such as language processing [21, 52–54], visual-visuospatial processing [47, 55], arithmetics [56], and memory [57, 58]. These studies have shown that fNIRS is a reliable and useful method for many experimental paradigms.

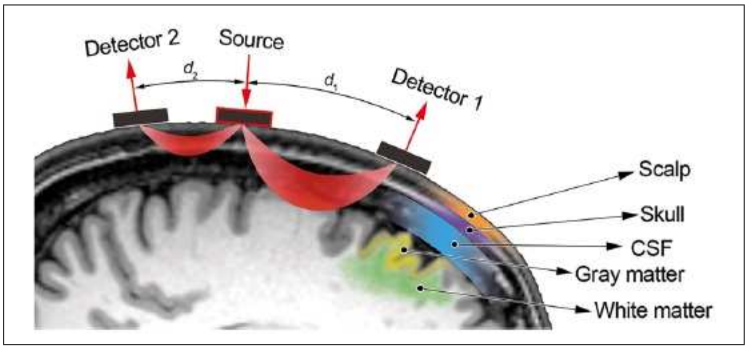

Figure 1.3 The propagation of the light from the source to the detector through the brain [3].

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1.3 Thesis Outline

Five different experiments have been carried out, and an infrared thermometer was developed within the scope of this thesis. The present dissertation includes the following chapters:

- **Chapter 1** summarizes the motivation and provides the general background for the methods used in the present dissertation.
- **Chapter 2** includes three auditory experiments. Word lists consisting of Turkish and English words have been used in all experiments. TMT measurement was performed in the first and second experiments, while simultaneous TMT-fNIRS measurement was performed in the last experiment.
- **Chapter 3** includes two experiments with three tasks. In the first experiment, the TMT changes of the subjects were measured during a visual Go/No-Go task. In the second experiment, the subjects participated in mental rotation and sentence-level language processing tasks in a counterbalanced design, while the hemodynamics of their prefrontal cortex was measured with fNIRS.
- **Chapter 4** summarizes the findings and conclusions of the thesis.
- **Appendix** includes the full stimuli list used in the present dissertation and the novel thermometer development.

2. AUDITORY EXPERIMENTS

2.1 Background and Introduction

As already stated in Chapter 1, language processing mainly occurs in the left hemisphere and people have roughly the same neuronal resources for processing language. On the other hand, there are several thousand languages around the world with different linguistic features. And these differences may lead to advantages or disadvantages for their speakers in terms of the cognitive load. Language processing can be investigated in terms of phonetics, morphology, syntax, or at different levels such as words or discourse. In the present chapter, processing words from different languages has been compared.

Interlingual words are widely used in cross-linguistic studies such as word recognition [59–62], priming [63], picture naming [64,65], and translation [66,67]. Interlingual words can be divided into three main categories: cognates, interlingual homographs (ILHGs), and interlingual homophones (ILHPs). Cognates can be defined as having the same meaning and orthography and/or phonology in at least two languages. Interlingual homograph words have the same orthography across languages but differ in their meaning, while interlingual homophone words have common phonology across languages but differ in their meaning. It is widely accepted that word processing in bilinguals is a language non-selective process [59, 60, 62, 68, 69]. Language non-selective view suggests that both language systems are automatically activated in the brain when a bilingual person is exposed to a written or spoken interlingual word. Wang et al. (2020) stated that automatic activation of both language systems can lead to faster or slower processing of interlingual words depending on the context and the experimental design [70]. In other words, two language systems activated by an interlingual word can either cooperate and trigger or strengthen the activity of each other to process the word or compete with each other to process the word on its own. In the first case, processing facilitation can be expected, while processing inhibition can be expected in the second case. Cognate, ILHG, and ILHP processing can be investigated based on language non-selective view. Studies have shown that cognate processing is faster than monolingual word processing [59, 71, 72]. Given that the cognates share orthography (and/or phonology) and meaning across languages, it is very likely that two language systems cooperate and lead to facilitation. On the other hand, studies have found that processing interlingual homograph words is harder to process than monolingual words [60,62,73], probably due to competition between the language systems. Although there is a controversy [68, 74, 75], processing interlingual homophone words has been reported to be more difficult than processing monolingual control words [61, 69, 76, 77]. Several studies have reported slower decision times or inhibitory effects for interlingual homophone processing. For example, it was shown that auditory recognition of interlingual homophones was affected by the native language of the subjects [61]. The authors found that monolingual subjects were faster than bilinguals in recognizing the interlingual homophones. They suggested that both representations of interlingual homophone words compete with each other to be selected, causing a conflict in the brain. This conflict needs to be resolved before a judgment is made about the language membership of the words, which causes slower responses from bilinguals. Lagrou et al. (2011) also demonstrated that bilinguals process interlingual homophone words more slowly and make more mistakes than control words in a lexical decision task [69]. Other studies have also reported slower processing of interlingual homophone words [76, 77].

The main aim of the present thesis was to compare English and Turkish languages at the word processing levels. To that end, three auditory word recognition experiments were carried out and reported in this chapter. The stimuli used in these experiments was a word list consisting of Turkish and English words. Moreover, English words were chosen from Turkish-English interlingual homophone words to increase the task difficulty and provoke greater neuronal activity in the brain.

2.2 Chapter Overview

This chapter covers the following experiments:

- **Word Level Auditory Experiment 1:** Forty-four subjects were randomly assigned to one of two groups (Control and Word). The subjects listened to a mixed word list consisting of 20 Turkish and 9 English words. Tympanic membrane temperatures of both ears were continuously recorded throughout the experiment.

- **Word Level Auditory Experiment 2:** Sixty subjects were randomly assigned to one of three groups (Control, Word, and Number). The subjects listened to a mixed word list consisting of 20 Turkish and 10 English words. Tympanic membrane temperatures of both ears were continuously recorded during the experiment. This study was presented as a poster during the 2015 European Brain Behaviour Society-European Behavioural Pharmacology Society Joint Meeting.

- **Simultaneous TMT and fNIRS Experiment:** Forty-two subjects were randomly assigned to one of three groups (Control, Word, and Number). The subjects listened to a mixed word list consisting of the same Turkish and English words with ***Word Level Auditory Experiment 2***. Tympanic membrane temperatures of both ears and fNIRS activity of the prefrontal cortex were simultaneously recorded throughout the experiment. This study was orally presented during the 2017 National Neuroscience Congress. fNIRS findings were also submitted to the European Journal of Neuroscience as a research paper.

Detailed explanations of methods, analysis, and results are provided in the relevant subsections.

2.3 TMT Experiments

2.3.1 Introduction for TMT-Word Processing Studies

A summary of the relevant literature about ear temperature measurement techniques has already been provided earlier. Therefore, a literature review of TMT studies that include language or word processing tasks is provided here.

One of the first TMT studies on language processing was carried out by Swift and Perlman in 1985 [34]. In this study, the authors asked 22 high school students to perform a face and non-word recognition task. A target set of three non-words were shown to the subjects, followed by the presentation of six response words. Subjects needed to respond whether the words from the response set were included in the target set. Mean temperature and mean minus base temperature was computed for the tasks. The results showed a non-significant slight tendency towards better performance in language tasks with higher left ear temperature. The authors have claimed that the verbal task might not have elicited a significant result because the stimuli consisted of non-words, which might have led subjects to perceive and process the stimuli either as visual or linguistic. In a subsequent study, Swift (1991) asked subjects to perform lexical decision and face recognition tasks [35]. In the lexical decision task, stimuli were composed of word pairs, half of which included a correctly spelled word and the other half did not. Subjects were required to give a 'yes' answer if the word pair included a correctly spelled word and 'no' if the words were not spelled correctly. She carried out the study with two groups of participants: eighteen and twenty-two, respectively. The first group was asked to respond as quickly as possible, while the second group was asked to maximize the response accuracy. Even though the findings were not statistically significant, the majority of the participants showed a left hemispheric bias for the word recognition task, which means that the left ear temperature was higher than that of the right hemisphere. The author also concluded that the performance of the subjects depends on the active hemisphere. Cherbuin and Brinkman (2004) also used verbal and visuospatial paradigms [25]. In this study, the participants were asked to mentally fold unfolded cubes (similar to cross sign formed by six adjacent squares) for the visuospatial paradigm, while they were asked to decide whether a cue word rhymes with a target word in the language processing paradigm. Their results demonstrated that the average tympanic temperature was significantly reduced during the task compared to baseline. Furthermore, they found that the rhyming task caused a significantly greater temperature decrease in the left ear than the right ear.

Cherbuin and Brinkman (2007) claimed that the contradictory findings of these studies were due to the fact that Cherbuin and Brinkman (2004) used an infrared thermometer which measures the temperature changes in the internal carotid artery, while the other studies measured the ear canal temperature, which has an independent dynamics than tympanum [37]. As stated in the previous chapter, the thermal dynamics of the ear canal can be different than that of the tympanic membrane, thus the measurement technique can have a significant effect on the results.

2.3.2 Word Level Auditory Experiment 1

Hypotheses.

The present experiment aimed to assess the cognitive loads and energy dynamics of processing words from native and non-native languages. To that end, a word list consisting of non-target Turkish and target interlingual English words were created. Subjects were divided into two groups with different tasks: passive listening (control group) and target word memorizing (word group). The ear temperatures of subjects were continuously recorded throughout the experiment. Given that both groups were going to listen to a word list, it was expected to find greater temperature changes in the left ears of the subjects compared to the right ear. The other expectation was to find greater temperature change in the word group compared to the control group since the word group was asked to perform a specific task. Lastly, it was expected that target English words would cause greater temperature changes than non-target Turkish words.

Materials and Method.

Forty-four undergraduate students attending either PSY 101 (Introduction to Psychology) or PSY 241 (Social Psychology) lectures at Boğazici University were recruited for the study via a public announcement. The subjects were randomly assigned to either control (C) or word (W) groups each with 22 subjects. The control group had 15 females and 7 males, while there were 19 females and 3 males in the word group. The mean age was 20.95 ± 1.97, and 20.68 ± 1.49 for control and word groups, respectively. Three subjects were left-handed in the control group, while all subjects were right-handed in the word group. Subjects were informed and gave written consent before the experiment. The study was approved by the local ethical committee, the Human Research Ethical Committee of Boğaziçi University.

Left and right ear temperatures were continuously and simultaneously recorded during the experiment via a custom-made ear temperature device [78]. The device consisted of two DS18B20 (Microchip Technology, USA) temperature sensors, a PIC18F2550 SMD microcontroller (Microchip Technology, Arizona USA), and an EGBT-04S Bluetooth module (e-Gizmo Mechatronix Central, USA) (Figure 2.1). The physical dimensions of the temperature sensors were suitable for fitting into the ear canal. The system had a sensitivity of 0.0625 °C, an accuracy of ± 0.1 °C, and a sampling rate of approximately 0.6 Hz. Temperature data were sent to a computer via Bluetooth.

Figure 2.1 Ear temperature measurement device.

The stimuli were a word list consisting of randomly ordered nineteen Turkish and ten English monosyllabic words. The complete word list can be seen in Table 2.1. The word list with the order of presentation in the experiment and the translations of the words are provided in Appendix Table A.1. English words were chosen as interlingual homophones. Therefore, subjects had to pay attention to these words to decide whether they were Turkish or English. On the other hand, Turkish words were easier to distinguish as they had meaning only in Turkish. The interstimulus interval was 16 seconds, as it was shown that it takes approximately 6-8 seconds for blood to reach the activated region of the brain [79]. The word list was vocalized by a female native speaker of Turkish.

Table 2.1
Word list consisted of 19 Turkish and 10 English words.

Turkish		English
Göz	Zar	Gene
Genç	Çöl	Short
Kalp	Bal	Cell
Tuz	Muz	Leaf
Tül	Kuş	Shark
Süt	Taş	Pie
Naz	Çöp	Fish
Sis	Saz	Car
Yurt	Ders	Boy
Kış		Shop

Experiments were carried out in a dimly lit, silent room. The ambient temperature was controlled with an air conditioning system and set within the range of 20-25° Celsius. The word list was played via a computer equipped with stereo speakers, placed on the right and the left of the subjects at a distance of 60 cm. After the acquisition of demographic data, the experimental protocol was explained in detail to each subject. Subsequently, group-specific instructions were given before the experiment to each subject. The control group was asked to listen to the list, while the word group was told that they would be asked to write down the English words from the list at the end of the experiment.

The sensors were placed in the ear canals of subjects following the instructions. Then, subjects were told to sit silently and motionless as much as possible to allow for sensors to reach an equilibrium temperature with ear canals (i.e., tympanic membrane). Simultaneously stabilized temperature recordings of both ears for at least twenty seconds was required for reaching the equilibrium [34] to start the experiment. Once the equilibrium was achieved, the subject was informed that the experiment had started and simultaneously the word list was played. Subsequently, paper and pen were provided to the subjects of the word group and they were asked to write the English words they remember from the list.

Analysis

The number of words remembered by each subject was recorded in the word group.

Baseline Analysis

Within-group and between-group analyses were performed. The temperature values of the left and right ears just before the experiment began were recorded as baseline TMT values. Then, the baseline temperature difference between the left and right ear was calculated for each subject with the following equation:

$$T_{base} = T_{left,base} - T_{right,base} \tag{2.1}$$

where $T_{left,base}$ is the baseline temperature of the left ear, and $T_{right,base}$ is the baseline temperature of the right ear. *Baseline* data set was created for each group by using the T_{base} values of the subjects.

Last-Base Analysis

Change in the temperature from the beginning to the end of the experiment was calculated for each ear of each subject with the following equations:

$$T_{left} = T_{left,last} - T_{left,base} \tag{2.2}$$

$$T_{right} = T_{right,last} - T_{right,base} \tag{2.3}$$

where $T_{left,last}$ is the left ear's temperature at the end of the experiment and $T_{left,base}$ is the baseline temperature of the left ear; while $T_{right,last}$ is the right ear's temperature at the end of the experiment and $T_{right,base}$ is the baseline temperature of the right ear. Lastly, the difference between the temperature increase (or decrease) of left and right ears during the experiment was calculated for each subject with the following equation:

$$T_{diff} = T_{left} - T_{right} \tag{2.4}$$

Therefore, T_{diff} data set reflects the lateralized temperature changes in ears during the experiment.

To sum up, two data sets were created for the analysis:

- ***Baseline***: For both groups, 22×1 vector consisting of the temperature difference between the left and right ear at the onset of the experiment.
- ***Last-Base***: For both groups, 22×1 vector consisting of the difference between the left and right ear's temperature increase (or decrease) from onset to the end of the experiment.

One sample and paired sample student t-tests were used for within-group analysis, while two sample student t-test was used for between-group analysis. All analyses were performed with MATLAB R2017B.

Results.

The subjects in the word group remembered 6.36 ± 1.53 words on the average.

Baseline Results

A paired-sample student's t-test showed no statistically significant difference in baseline temperatures of left and right ears for either the control ($t(21)=-0.949$, $p=0.353$) or the word ($t(21)=1.299$, $p=0.208$) groups.

Two sample student t-test failed to find a statistically significant difference between the groups in terms of baseline temperature (t(42)=-1.592, p=0.136).

Last-Base Results

The temperature trends of the groups can be seen in Figure 2.2. A paired-sample student's t-test was used for within-group statistical analysis. The difference between the left and right ears in terms of the temperature increase from the beginning to the end of the experiment was not statistically significant in any of the groups (t(21)=0.816, p=0.424 for control group; t(21)=-1.283, p=0.214 for word group) (Table 2.2). The temperature increase of the left ear was higher than that of the right ear in the control group from onset to the end of the experiment, a case reversed in the word group (Figure 2.3).

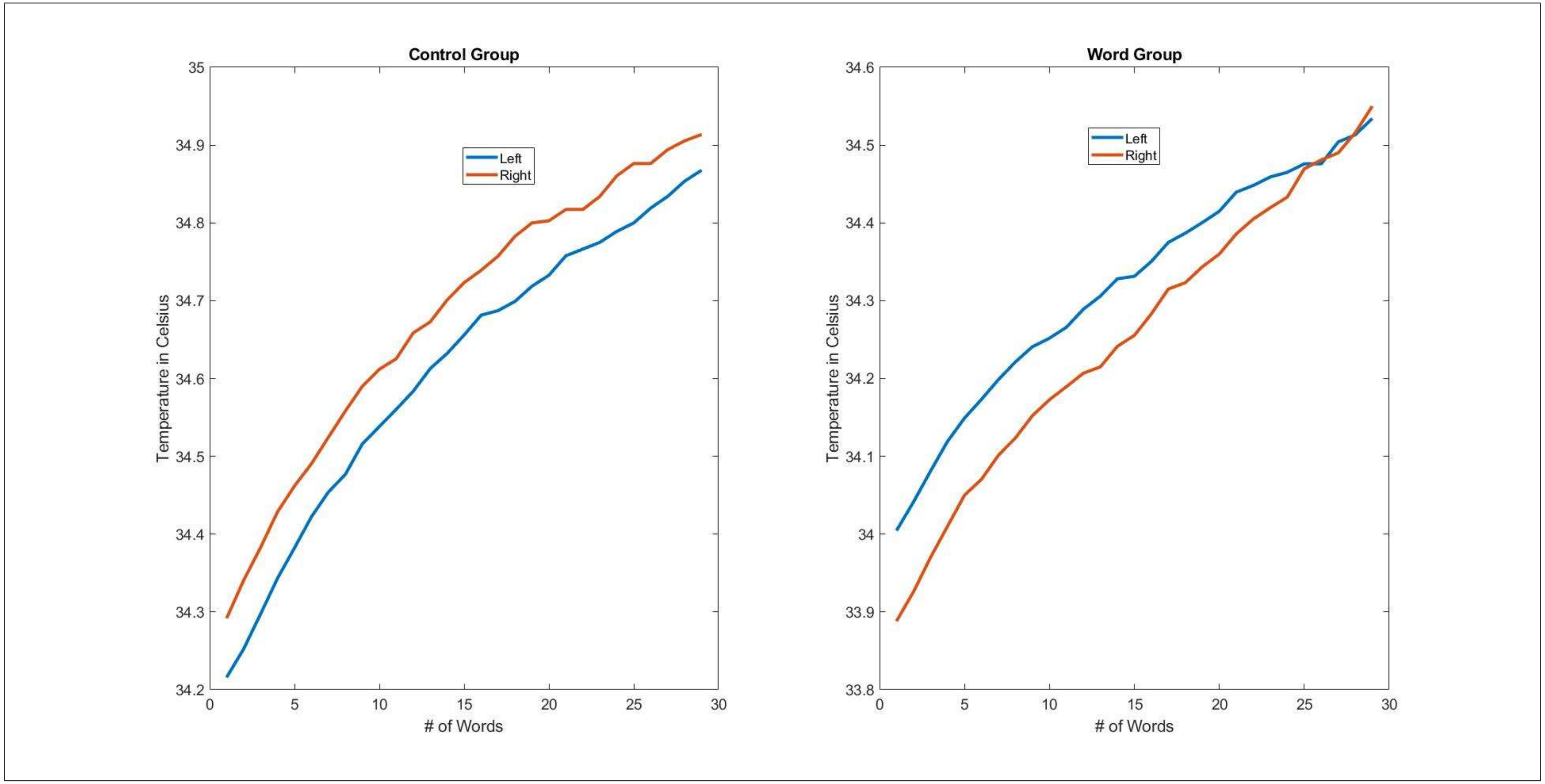

Figure 2.2 The temperature changes in Control (left) and Word (right) groups during the experiment.

Two sample student t-test was used for between-group analysis. There was no statistically significant difference between the groups in terms of the temperature difference calculated as left minus right ear from onset to the end of the experiment (t(42)=520, p=0.136) (see Eq.s 2.2, 2.3, and 2.4).

Table 2.2
Mean temperature changes from beginning to the end of the experiment in degrees of Celsius.

Group	**Left Ear**	**Right Ear**	**L-R Difference**
Control	0.706	0.656	0.050
Word	0.546	0.678	-0.131

To sum up:

- There was no difference between groups at the outset of the experiment.
- The left ear presented a non-significant higher temperature increase than the right ear in the control group during the experiment (Table 2.2).
- The right ear presented a non-significant higher temperature increase than the left ear in the word group during the experiment (Table 2.2).
- The groups did not significantly differ in terms of the temperature increase difference calculated as left minus right throughout the experiment.

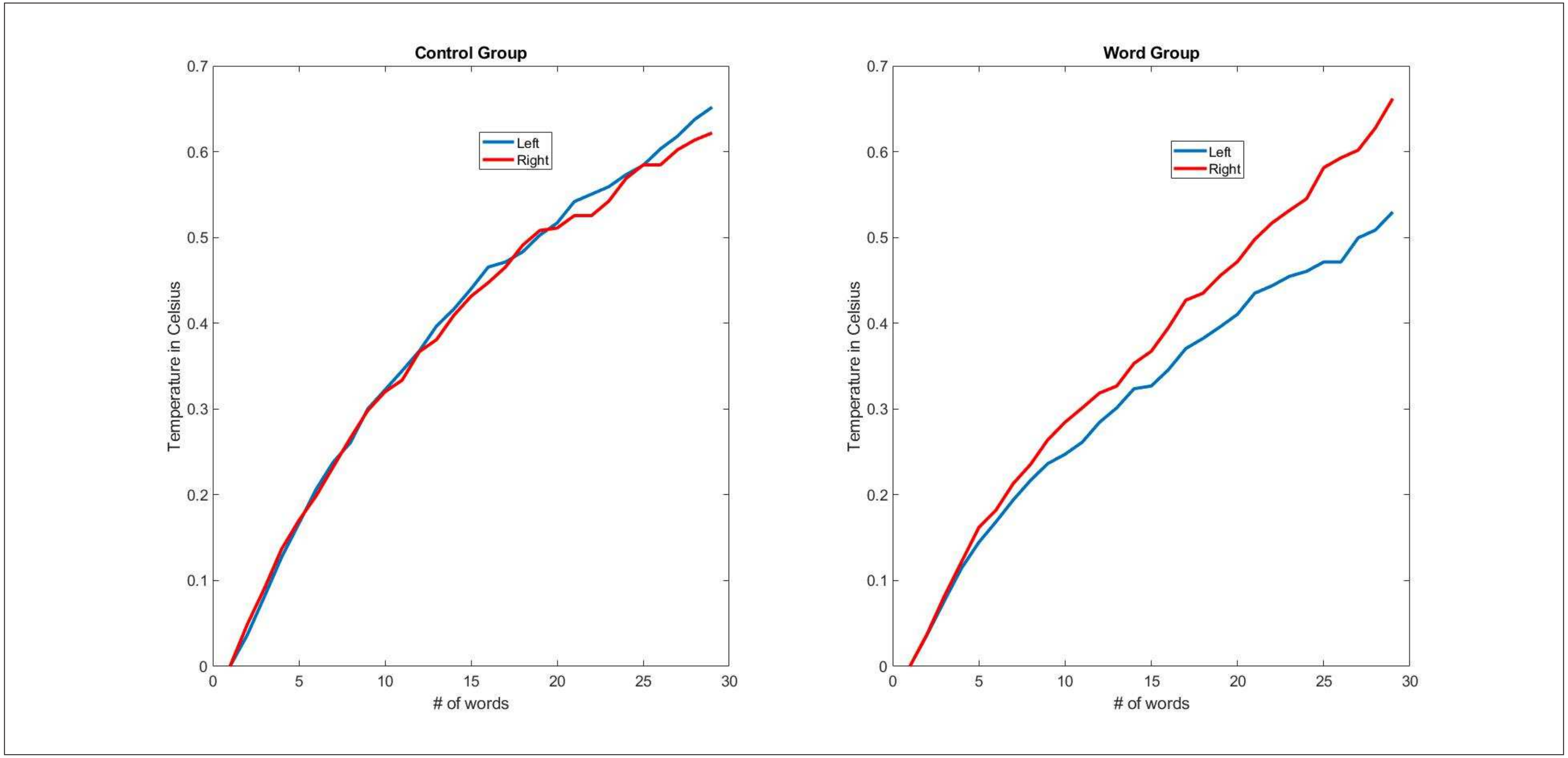

Figure 2.3 The temperature changes from the baseline temperatures in Control (left) and Word (right) groups during the experiment.

Discussion.

In this experiment, the temperature changes caused by processing Turkish and English words were investigated. To that end, the participants were divided into two groups with different tasks. One group was asked to perform passive listening, while the other group was asked to memorize English words while ear temperatures were continuously recorded.

The average number of remembered words suggests that the subjects of the word group followed the instructions. Within-group and between-group baseline results showed that none of the groups had an ear temperature bias at the onset of the experiment.

It is known that the left hemisphere is involved in language processing [5, 6, 80]. Therefore, the temperature difference between ears was expected to reflect the differential activity of the hemispheres, especially in the word group. As explained in Section 1.2.1.1 *Ear Temperature*, two theories have been suggested to explain the relationship between the hemispheric activity and the ipsilateral ear temperature changes: increased temperature with increased hemispheric activity [35] and decreased temperature with increased hemispheric activity [25]. In the present study, both groups showed temperature increase throughout the experiment, favoring the increased temperature-increased brain activity theory. Based on this, a greater (Left-Right) temperature difference in the word group than the control group would be expected. However, the findings showed that the word group showed a greater temperature increase in the right ear, which was unexpected. This experiment was carried out as a pilot study. One possible confounding factor could be the composition of the word list. Studies have shown that word frequency can affect word processing [81–83]. In this experiment, English and Turkish words were not matched in their frequencies. Unfortunately, most of the Turkish words in the list were not present in the relevant sources, such as Göz (2003) [84] and Tekcan and Göz (2005) [85]. Thus, a valid comparison between the frequencies of the words was not possible.

Therefore, it was decided to repeat the experiment by adding another experimental group and changing the word list.

2.3.3 Word Level Auditory Experiment 2

Hypotheses.

In the previous experiment, the right ear temperature increase was greater than that of the left ear in the word group. This result was unexpected. Moreover, the frequency of target and non-target words were not matched. Last but not least, it might not be the best practice to compare the word group with the control group in terms of task difficulty, as one can not be sure whether the control group participants actually listened and paid attention to the list. Therefore, it was decided to repeat the previous experiment with the following improvements:

- Inclusion of a novel experimental group that was asked to count the number of target words from the list.
- Matching the frequencies of target and non-target words

The number group would allow comparing groups in terms of task difficulty since they were asked only to memorize the number of target words. Obviously, this task would be less difficult than that of the word group and more difficult than that of the control group, allowing a more controlled comparison.

The aim of the present experiment was also to assess the cognitive loads and energy dynamics of processing words from native and non-native languages in a better, more controlled experimental design. For this purpose, a new word list consisting of non-target Turkish and target interlingual English words were created. There were three experimental groups in this experiment: the control (passive listening), the word (target word memorizing), and the number (target word counting). The ear temperatures of subjects were continuously recorded throughout the experiment. Hypotheses were the same with the previous experiment: i) greater temperature changes in the left ears of the subjects compared to the right ear; ii) greater temperature change in the word group compared to the control and the number groups; iii) greater temperature changes for processing target English words compared to non-target Turkish words.

Materials and Method.

Sixty undergraduate students attending either PSY 101 (Introduction to Psychology) or PSY 241 (Social Psychology) lectures in Boğazici University were recruited for the study via a public announcement. The subjects were randomly assigned to one of the following groups: control (C), word (W), and number (N), each group with twenty subjects. The control group had thirteen females and seven males; the word group had fifteen females and five males; the number group had eleven females and nine males. The mean age was 20.65 ± 1.88, 19.9 ± 1.22, and 19.89 ± 1.25 for control, word, and number groups, respectively. The control group had one left-handed subject, while the word group had three, and the number group had four left-handed subjects. Subjects were informed and gave written consent before the experiment. The study was approved by the local ethical committee, the Human Research Ethical Committee of Boğaziçi University.

The TMT measurement device (Figure 2.1) used in Section 2.3.2 Auditory Word Level Experiment 1 was also utilized in this experiment to record the ear temperature of the subjects.

The stimuli were a word list consisting of randomly ordered twenty Turkish and ten English monosyllabic words. The complete word list can be seen in Table 2.3. The word list with the order of presentation in the experiment, the word frequencies, and the translations were provided in Appendix Table A.2. English (i.e., target) words were also interlingual homophone words. Furthermore, Turkish and English words were matched for the frequency of use in their respective languages in the present experiment. Turkish frequencies were retrieved from Göz (2003) [84], while English frequencies from

Leech et al. (2014) [86]. The inter stimulus interval (ISI) was increased to 20 seconds in this experiment to create a longer post-stimulus relaxation interval, enabling more precise analysis. The word list was vocalized by the same Turkish native-speaker female colleague.

Table 2.3
The word list consisted of 20 Turkish and 10 English words.

Turkish		English
Kıl	Suç	Boy
Sır	Çöp	Bye
Tüy	Dev	Ten
Boş	Tıp	Dish
Ses	Kuş	Bell
Gül	Yaz	Phone
Dün	Süt	Pie
Çay	Cep	Ball
Tuz	Kaş	Car
Zar	Kök	Tell

Experiments were carried out in a dimly lit, silent room. The ambient temperature was controlled with an air conditioning system and set within the range of 20-25° Celsius. The word list was played via a computer equipped with stereo speakers that were placed on the right and the left of the subjects at a distance of 60 cm. After the acquisition of demographics, the experimental protocol was explained in detail to each subject. Subsequently, group-specific instructions were given before the experiment to each subject. The instructions for the control and word groups were the same as the previous experiment (see Section 2.3.2 Auditory Word Level Experiment 1). The number group was asked to remember the number of English words from the list.

The sensors were placed in the ear canals of subjects following the instructions. Then, subjects were told to sit silently and motionless as much as possible to allow for sensors to reach an equilibrium temperature with ear canals (i.e., tympanic membrane). Simultaneously stabilized temperature recordings of both ears for at least twenty seconds was required for reaching the equilibrium [34] to start the experiment. Once the equilibrium was achieved, the subject was informed that the experiment had started and simultaneously the word list was played. At the end of the experiment, paper and pen were provided to the subjects of the word group and they were asked to write the English words they remember from the list. For the number group, subjects were asked to report the number of English words they heard during the experiment.

Analysis

For the word group, words remembered by each subject were recorded, while the number of reported items by the subjects were recorded for the number group. Since the data was non-parametric, Wilcoxon rank-sum test was used to assess the task difficulty difference between the word and number groups.

Within-group and between-group analyses were performed on the temperature data. *Baseline* and *Last-Base* data sets were created for this experiment following the steps and equations explained in Section 2.3.2 Auditory Word Level Experiment 1. These data sets are summarized below.

A third data set, called *Post-Pre*, was created for this experiment with the following steps: 1. 20 seconds long ISI between each word pair was divided into two equal 10 seconds long intervals; 2. The first 10 seconds long interval after each word was labeled as *post-stimulus*, while the second 10 seconds long interval was labeled the *pre-stimulus* for the next word (Figure 2.4); 3. Mean temperatures of pre-stimulus and post-stimulus windows were calculated for each word by averaging the 10 seconds long segments; 4. The temperature difference caused by a single word was calculated by subtracting the pre-stimulus mean temperature from the post-stimulus mean temperature for both ears in each subject. 5. Temperature differences were averaged across subjects to obtain a single temperature difference for each word for both ears within the groups. 6. The vector consisted of the right ear's temperature changes was subtracted from the vector consisted of the left ear's temperature changes.

To sum up, three data sets were created for the analysis:

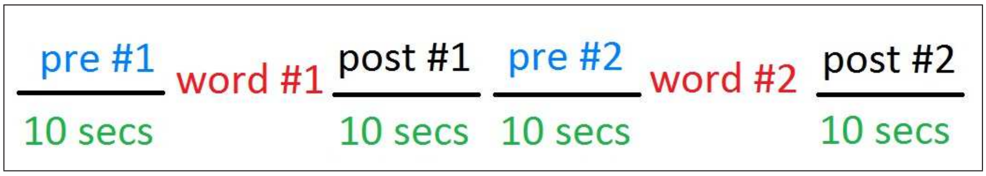

Figure 2.4 Data parsing for *Post-Pre* data set.

- ***Baseline***: For each group, a 20×1 vector consisting of the temperature difference between the left and the right ear at the onset of the experiment.
- ***Last-Base***: For each group, a 20×1 vector consisting of the difference between the left and right ear's temperature increase (or decrease) from onset to the end of the experiment.
- ***Post-Pre***: For each group, a 30× 1 vector consisting of the average temperature difference between the left and right ears caused by each word.

One sample student t-test was used for the within-group analysis of *Baseline*, *Last-Base*, and *Post-Pre* data sets. Between-group analyses were performed with one-way ANOVA. All statistical analyses were performed in MATLAB R2017B.

Results.

The word group remembered 6.30 ± 1.98 words on average, while the number group reported an average of 8.85 ± 2.70 English words. Wilcoxon rank-sum test revealed a statistically significant difference between the word and number groups (Z=3.06, p=0.002).

Baseline Results

Paired sample student's t-test analysis revealed no statistically significant difference between the baseline temperatures of left and right ears in any of the groups (t(19)=-1.089, p=0.290 for control group; t(19)=0.193, p=0.849 for word group; t(19)=0.040, p=0.968 for number group). One-way ANOVA also failed to find a statistically significant difference among the groups in terms of baseline temperature difference (F(2,57)=0.29, p=0.749).

Last-Base Results

The difference between the left and right ear in terms of the temperature increase from the beginning to the end of the experiment was not statistically significant in any of the groups (t(19)=-0.474, p=0.639 for control group; t(19)=1.414, p=0.174 for word group; t(19)=-0.56, p=0.582 for number group). One-way ANOVA failed to find a statistically significant difference among the groups in terms of the temperature difference between left and right ears from beginning to the end of the experiment (F(2,57)=1.23, p=0.299). However, the word group had the greatest albeit non-significant difference between the left and right ears in terms of the temperature increase from the beginning to the end of the experiment (Table 2.4). The temperature increase in the left ear was higher than that of the right ear only in the word group (Figure 2.5).

Table 2.4
Mean temperature changes from beginning to the end of the experiment in Celsius degree calculated as Left Ear - Right Ear.

Group	L-R Difference
Control	-0.020
Word	0.106
Number	-0.057

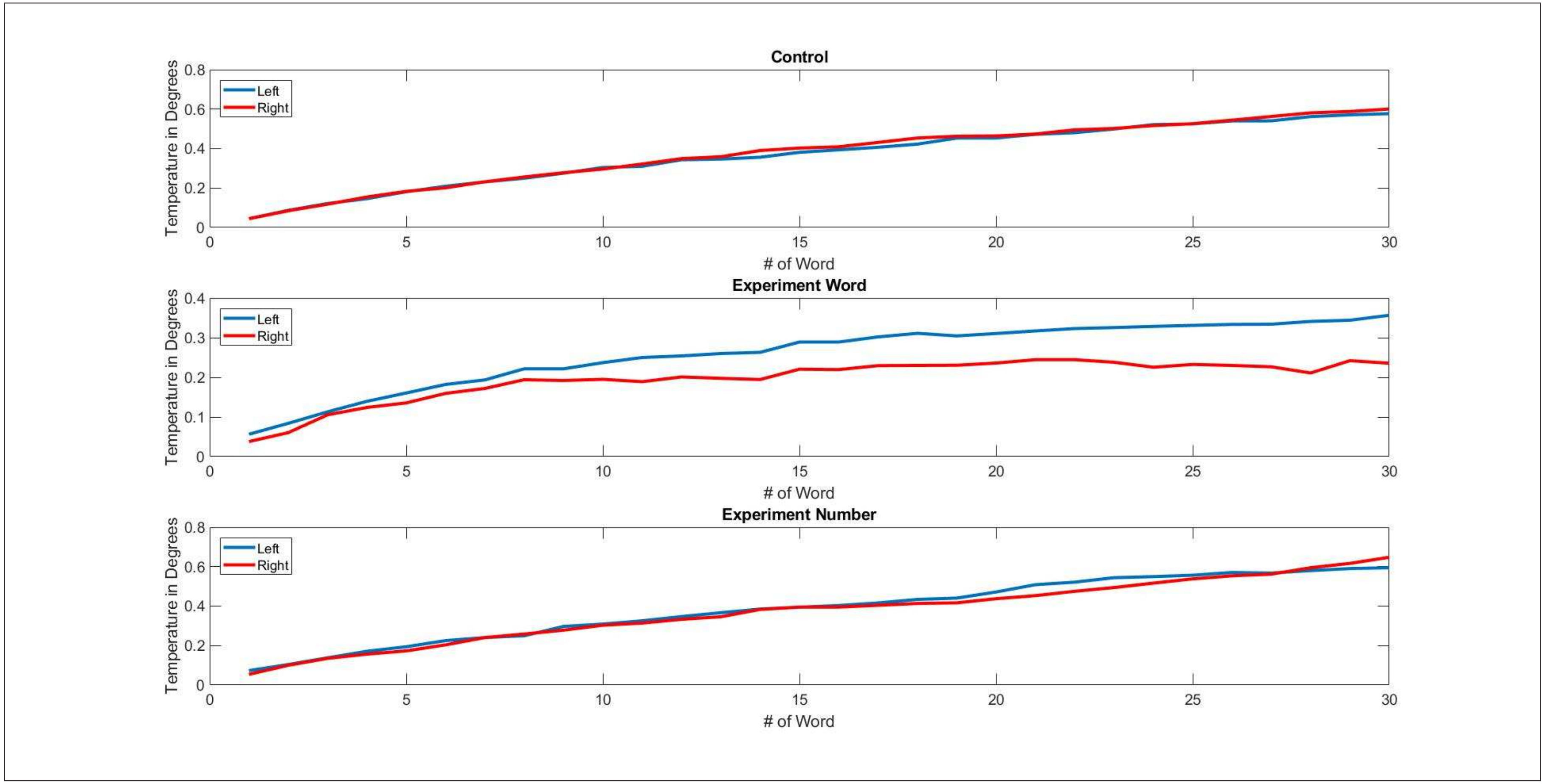

Figure 2.5 The temperature changes from baseline temperature, in Control (top), Word (middle), and Number (bottom) groups during the experiment.

Post-Pre Results

One sample student t-test revealed a statistically significant difference between the left and right ears' temperature increase after a word only in the word group ($t(29)=3.592$, $p=0.001$). The average temperature increase after a word was 0.008 ± 0.001°C and 0.004 ± 0.001°C for left and right ears, respectively. The control group ($t(29)=0.029$, $p=0.977$) and the number group ($t(29)=-1.006$, $p=0.323$) did not show statistically significant differences.

One-way ANOVA showed a significant difference among the groups in terms of the temperature difference between ears (calculated as left minus right) after a word ($F(2,87)=4.58$, $p=0.013$). Bonferroni corrected post-hoc t-test revealed that the word group had a significantly higher temperature difference, calculated as left minus right ears, than the number group ($p=0.012$). The word group also had a higher temperature difference, calculated as left - minus right, than the control group, but the difference was not significant ($p=0.137$). There was no statistically significant difference between the number and control groups.

Lastly, a paired sample student t-test was performed to assess whether Turkish and English words caused a temperature increase bias within the groups. However, there was no significant difference in any of the groups ($t(19)=0.698$, $p=0.494$ for control group; $t(19)=0.934$, $p=0.362$ for word group; $t(19)=0.652$, $p=0.522$ for number group).

To sum up:

- There was no statistically significant difference among the groups at the onset of the experiment.
- Even though the difference among the groups was not statistically significant, the word group had the greatest temperature increase difference between the left and right ears (calculated as left minus right) throughout the experiment (Table

2.4).

- Temperature increase difference between the left and right ears upon hearing a word caused a statistically significant difference only in the word group. The left ear presented a greater temperature increase than the right ear in the word group.

- Turkish and English words did not significantly differ in terms of temperature increase difference between the left and right ears in any of the groups.

Discussion.

The previous experiment had unexpectedly revealed a greater temperature increase in the right ear than the left ear for the word group. However, target and non-target words were not matched in terms of their frequency. Moreover, there were only two groups in the previous experiment. The control group was asked to perform passive listening, but it was not possible to check whether each participant followed these instructions and listened to the list in the control group. As a result, comparing word and control groups might not be informative about the true dynamics of processing words. Hence, another experimental group (i.e., the number group) was introduced in the present experiment. The task (i.e., target word recognition) of the number group required the participants to actively listen to the list. Moreover, the task was relatively easier and required less cognitive effort than that of the word group. Thus, it allowed more reliable task difficulty comparison for processing target and non-target words.

Based on the instructions and the tasks of the groups, Word > Number > Control was expected in terms of processing difficulty, reflected in ear temperature increase (calculated as left-minus-right) and number of reported items. Numerous studies have shown that accuracy (i.e., giving the correct response) decreases with the task difficulty [87–89]. It was assumed that the number of reported items reflected the task difficulty (thus, accuracy) in this experiment. The number of reported items by the word and the number group supported the expected task difficulty difference between the groups.

Baseline temperature analysis demonstrated that none of the groups had an ear temperature bias at the beginning of the experiment. Therefore, it can be said that within-group and between-group temperature differences were caused by the tasks. All groups showed a temperature increase during the experiment, supporting the increased activity-increased temperature theory. As in the previous experiment, it was expected to see a greater temperature increase in the left ear than the right ear in the word group. Table 2.4 confirmed that the left ear showed a greater temperature increase than the right ear. Swift (1991) has found that 12 out of 18 subjects presented a left ear temperature bias during a word recognition task [35]. On the other hand, Cherbuin and Brinkmann (2004) showed that the temperature decrease in the left ear was greater than that of in the right ear during a rhyming task [25], which seems to contradict Swift (1991). However, there was a core methodological difference between these studies. Swift (1991) measured the ear canal temperature in her study, while Cherbuin and Brinkman (2004) used an infrared temperature sensor to measure the tympanic temperature. Cherbuin and Brinkman (2007) [37] and Lorr et al. (2017) [43] have warned against the thermal contamination of the ear canal while measuring ear temperature and claimed that the ear canal temperature could increase upon an ipsilateral hemisphere activation, despite a decrease in tympanic membrane temperature due to the increased blood flow. In the present experiment, digital sensors were used to measure ear temperature. Therefore, temperature measurements could have been affected mainly by the thermal dynamics of ear canals rather than of the tympanic membrane. Hence, it should be reasonable to expect an increase in the left ear's temperature more than the right ear's for word processing. Given the task differences between the word and the other two groups, it can be said that processing English interlingual homophone words cause stronger activation in the left hemisphere for the word group. On the contrary, the number group presented a slightly greater temperature increase in the right ear than the left ear. The number group was expected to present a greater temperature increase in the left ear compared to the right ear, to a lesser degree than the word group. However, different cognitive mechanisms induced by the task requirements of the number group could be responsible for the unexpected result. The main focus of the number group was identifying the target words, which requires robust conflict monitoring as the target words were interlingual homophones. It was shown that the right hemispheric activation is crucial for conflict resolution [90, 91]. Therefore, the neuronal activation in the right hemisphere could have become as strong as in the left hemisphere and altered ear temperature dynamics, resulting in an equal or even greater temperature increase in the right ear compared to the left ear. Indeed, the next experiment of the present dissertation found that the right hemisphere is strongly activated in the number group (further discussion on this will be covered in the next experiment's discussion).

Last-Base results revealed a greater temperature increase in the left ear compared to the right ear only in the word group. It can be claimed that processing words induced a significantly greater neuronal activity in the left hemisphere. It also suggests that processing English (or perhaps words from a non-native language) causes a greater cognitive load for the brain. Furthermore, a greater left minus right ear temperature increase of the word group compared to the other two groups also confirmed the initial hypothesis about the task difficulty. It has been expected to reveal a significant temperature difference between English and Turkish words, which was not present in this experiment. It should be noted that the present study aimed to induce and capture a within-task contrast (i.e., processing words from non-native and native languages), while previous studies contrasted two different cognitive skills, namely visual processing and language processing [25, 35], which were expected to induce a neuronal activation in the right and the left hemisphere, respectively. The sensitivity of the TMT measurement system used in the present dissertation was 0.0625° C. Even though this value is superior to that of the commercial thermometers, the temperature increase difference between processing Turkish and English might have caused a smaller temperature difference than this sensitivity value, resulting in a non-significant result. Thus, the sensitivity limitation of the recording system could be the reason for failing to achieve a significant difference between target and non-target words, and one may not expect to reveal a significant difference between processing target and non-target words in terms of temperature change without using an even superior thermometer. Another possibility could be that Turkish words might have caused more widespread activation in the brain, although processing English words was more difficult. Numerous studies have shown that high-frequency words are easier to process than low-frequency words [92–94]. However, Berglund-Barraza et al. (2019) found that high-frequency words caused a more widespread activity pattern in the prefrontal cortex compared to low-frequency words [95]. English and Turkish words were matched in their frequency in the present experiment. However, it could be claimed that the Turkish words have stronger and more widespread mental representations or neural connections than English words, as all participants were native Turkish speakers and had a greater familiarity with Turkish words. Therefore, hearing a Turkish word might have caused a neuronal activity in a higher number of cortical areas than an English word, which might cause a greater neuronal activity in less number of brain regions compared to Turkish words. Hence, the total blood flow towards the active hemisphere might not be significantly different for processing English and Turkish words, even though there is a significant processing difficulty. To rule out this possibility, similar experiments with native English speakers would be carried out. Moreover, some studies have shown that the right frontal regions are involved especially in language processing in a bilingual context [96, 97]. Therefore, right hemispheric activity during English word processing might have reduced or prevented a robust left-lateralized neuronal response, thus preventing a significant difference between Turkish and English words.

Lastly, the event-related design of the experiment can be the reason for failing to achieve significant Turkish vs. English word processing difference. Inter-stimulus-interval of the experiment was set as 20 seconds to allow for sufficient neuronal relaxation. However, it is possible that the temperature changes might have caused by the cumulative effect of the words. A block-design experiment might reveal this contrast.

This experiment showed that ear temperature measurement reflects the differential hemispheric activity during word processing. There was no English vs. Turkish contrast in terms of temperature difference in any of the groups. The reason could be that the TMT system used in this experiment might not be sensitive enough to capture the brain activity-induced within-subject temperature changes in an event-related design. It is likely that a system measuring ear temperature directly from the tympanum (e.g., an infrared sensor system) with superior technical specifications can capture such difference. Moreover, the event-related design of the experiment can lead to a cumulative effect in temperature changes, which can prevent the observation of a significant contrast between processing target and non-target words. Thus, a block-design experiment (in which, for example, blocks consisting of only Turkish words and blocks consisting of only English words) can reveal within-subject differences. All in all, the overall activity results of the present study indicated that the temperature differences between the left and the right ear become significant as the task difficulty increases (word $>$ control and number).

2.4 Simultaneous TMT and fNRIS Experiment

The previous experiment indicated that processing words from a non-native language causes a greater temperature increase in the left ear. As stated above, the temperature changes depend on both the heat dissipated from the active brain region and the blood flow towards that region. As also stated above, fNIRS measures neuronal activity based on the blood flow dynamics. Therefore, simultaneous fNIRS-TMT measurement would be valuable to show that a relatively novel TMT method is a valid and reliable method for assessing cognitive performance. Hence, it was decided to repeat the previous experiment with new participants to investigate the relationship between fNIRS recordings and TMT recordings.

2.4.1 Introduction for fNIRS-Word Processing Studies

The pertinent interlingual word processing literature was provided in the previous section. In this section, the word processing experiments carried out with fNIRS are summarized.

Kovelman et al. (2008) have used fNIRS recordings to compare the semantic judgment performances of monolingual and bilingual adults in monolingual and bilingual contexts and found that bilinguals presented right DLPFC activation in bilingual context [98]. A word definition task carried out with fNIRS in the Japanese/Chinese context showed that increased left DLPFC activity in bilinguals is associated with preventing the non-target language semantic of the words, while the right DLPFC activity is associated with focusing on the target language [99]. Another fNIRS study has also shown that elementary school students, who have been learning a second language, showed greater left-hemispheric activation for words from their native language (classified as high-frequency words) and greater right-hemispheric activity for processing words from their second language (classified as low-frequency words) [100]. The authors have also stated that the subjects processed words from their second language as non-word auditory stimuli. Fishburn et al. (2014) demonstrated that the activity in the left and right DLPFC increases with the working memory load in an n-back memory test [101], while Amiri et al. (2014) have shown that bilateral DLPFC activation increased with age in a lexical decision task [102]. A more recent fNIRS research comparing the cognitive loads of high-frequency and low-frequency words in an auditory verbal working memory task found that high-frequency words invoked a greater activity than low-frequency words in prefrontal regions, as opposed to the expectations [95]. Lastly, Arredondo et al. (2019) found that monolingual children showed greater neuronal activation in the left hemisphere when compared to bilingual children in an English lexical decision task, which included auditory competitor and non-competitor words [103]. In summary, these studies have shown that left DLPFC plays a significant role in word processing in different languages. However, it should be noted that right DLPFC activity becomes significant if the subjects are bilingual or the experiment is designed in a bilingual context. Therefore, any word-level language processing study should assess the activity of both left and right hemispheres.

Hypotheses.

The previous experiment demonstrated a greater temperature increase in the left ear of the word group compared to the right ear. In the present experiment, the main aim was to investigate the relationship or a possible correlation between fNIRS and TMT methods, since both methods depend on blood flow. Showing that the TMT findings are correlated or in line with more robust fNIRS method would strengthen the power and the reliability of the relatively novel TMT method. The tasks of the groups were the same with the previous experiment. The only difference was performing simultaneous fNIRS and TMT recordings throughout the experiment. Thus, the temperature-related hypotheses were also the same with the previous experiment; i.e., greater temperature change in the left ear than the right ear, greater temperature change in the word group, and greater temperature change for English words. Hypotheses regarding fNIRS were similar to those of TMT. The first hypothesis was to find a greater hemodynamic activity in the left hemisphere compared to the right hemisphere, as the task was word processing. Secondly, it was hypothesized that the word group would have shown the greater hemodynamic activity. The last hypothesis was that English words would cause greater hemodynamic activity than Turkish words.

2.4.2 Materials and Method

Forty-two undergraduate students attending either PSY 101 (Introduction to Psychology) or PSY 241 (Social Psychology) lectures at Boğazici University were recruited for the study via a public announcement. The subjects were randomly assigned to one of the following groups: control (C), word (W), and number (N) groups, each with 14 subjects. The control and word groups had three males and eleven females, while the number group had five males and nine females. The mean age was 20.48 ± 1.62, 20.66 ± 1.02, and 20.15 ± 1.22 for control, word, and number groups, respectively. The control and number groups had one left-handed subject each, while the word group had two left-handed subjects. All subjects were informed before the experiment and gave written consent. The study was approved by the local ethical committee, the Human Research Ethical Committee of Boğaziçi University.

Tympanic membrane temperature of both ears and hemodynamic activity of the frontal cortex were simultaneously recorded throughout the experiment. The TMT device (Figure 2.1) from the previous experiments was used in this experiment. For the hemodynamic activity of the frontal regions, a functional Near-Infrared Spectroscopy measurement system (ARGES CEREBRO) (Figure 2.6) developed by Hemosoft Bilişim ve Egitim Hizmetleri A.Ş. was used. The device, equipped with 16 channels consisting of four light sources (735 and 850 nm) and 10 detectors covering the frontal cortex, was used to collect hemodynamic data (Figure 2.7). The sampling rate of the system was 2.5 Hz and the source-detector distance was 2.5 cm.

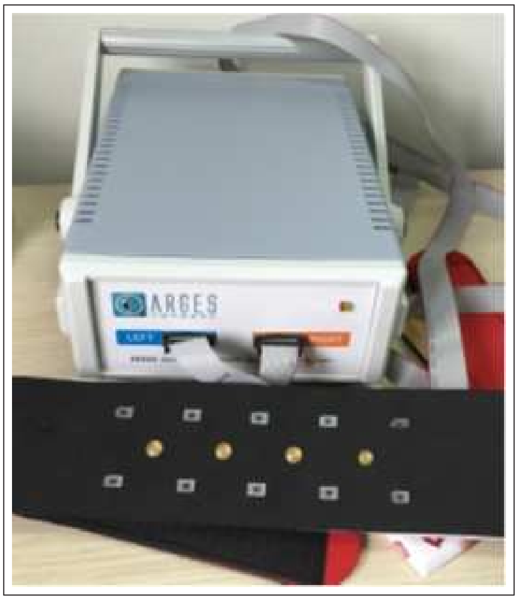

Figure 2.6 16 channels NIRS recording system.

The stimuli and the experimental design were the same as in the experimental design used in Section 2.3.3 Auditory Word Level Experiment 2.

Experiments were carried out in a dimly lit, silent room. The ambient temperature was set within the range of 20-25° Celsius via an air conditioner system. The word list was played via a computer equipped with stereo speakers that were placed on the right and the left of the subjects at a distance of 60 cm. After the acquisition of demographics, the experimental protocol was explained in detail to each subject. Subsequently, group-specific instructions were given before the experiment to each subject. The instructions were the same as the previous experiment (Section 2.3.3 Auditory Word Level Experiment 2).

An fNIRS probe was placed on the forehead, and the sensors were placed in the

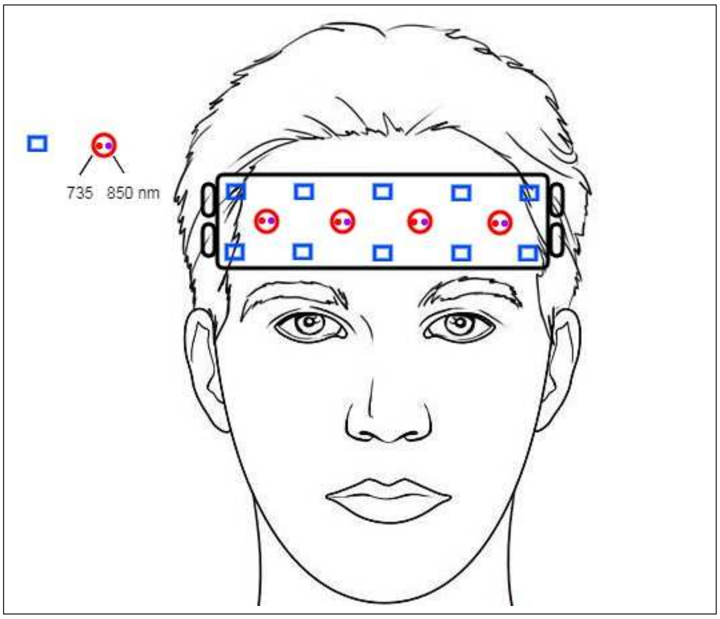

Figure 2.7 Probe structure of NIRS recording system. Each red dot corresponds to a LED source, while blue dots are detectors.

ear canals of the subjects following the instructions. Then, subjects were told to sit silently and motionless as much as possible to allow for sensors to reach an equilibrium temperature with ear canals (i.e., tympanic membrane). Simultaneously stabilized temperature recordings of both ears for at least twenty seconds was required for reaching the equilibrium [34] to start the experiment. Once the equilibrium was achieved, the subject was informed that the experiment had started, and simultaneously the word list was played. After the experiment, paper and pen were provided to subjects of the word group and they were asked to write the English words they remember from the list. For the number group, subjects were asked to report the number of English words they heard during the experiment.

Analysis.

The number of words remembered by each subject was recorded for word and number groups, separately. Since the data was non-parametric, Wilcoxon rank-sum test was used to assess the task difficulty difference between the word and number group.

TMT Analysis

The analysis method, outlined in the Analysis subsection of Section 2.3.3 Word Level Auditory Experiment 2, was also used in this experiment for TMT analysis.

The following data sets were created for TMT analysis:

- ***Baseline***: For each group, a 14×1 vector consisting of the temperature difference between the left and the right ear at the onset of the experiment.
- ***Last-Base***: For each group, a 14×1 vector consisting of the difference between the left and right ear's temperature increase (or decrease) from onset to the end of the experiment.
- ***Post-Pre***: For each group, a 30×1 vector consisting of the average temperature difference between the left and right ears caused by each word.

One sample student t-test was used for the within-group analysis of *Baseline*, *Last-Base*, and *Post-Pre* data sets. Between-group analyses were performed with one-way ANOVA. All statistical analyses were performed in MATLAB R2017B.

fNIRS Analysis

fNIRS recordings were preprocessed with a combination of custom-written MATLAB scripts and the functions of Homer2 Software [104] before analysis. The recording software provided raw optical intensity data for each channel. Channels with poor signal quality were detected based on coefficients of variation (CV) method [105, 106] with a threshold of 7.5% and excluded from the analysis. A preprocessing pipeline was created based on Homer2 functions. The raw optical intensities were converted into optical densities. Homer2 functions were used to create a preprocessing pipeline. The raw optical intensities were converted into optical densities. The *hmrMotionArtifact* function was used to identify and label the noisy segments. Motion artifacts were removed from the labeled segments via a principal component filter analysis (PCA) filter.

Subsequently, a third-order Butterworth bandpass filter with the cut-off frequencies of 0.01 Hz and 0.2 Hz was employed to eliminate the physiological noises such as Mayer waves (i.e., arterial blood pressure oscillations), respiration, and heartbeats. Lastly, denoised optical densities were converted into hemoglobin concentrations. Data analysis was performed with only oxyhemoglobin (HBO) concentrations, as it was claimed to reflect the neuronal activity better than HBR and HBT [107, 108].

Different peak latency values were reported for oxyhemoglobin concentration ranging from post-stimulus 2 seconds [109] to 12 seconds [110]. Therefore, approximately 14.5 second long segments, consisting of 2 seconds long pre-stimulus baseline period and a 12.5 seconds long post-stimulus activity period, were created for stimulus in each channel. Subsequently, each segment was detrended and classified as either belonging to a Turkish (non-target) word or an English (target) word. Segments were created in each channel for each subject. Then, the hemodynamic activity strength (HAS) parameter was calculated with the following equation:

$$HAS = \frac{Mean_{act} - Mean_{base}}{Std_{base}} \tag{2.5}$$

where $Mean_{act}$ corresponds to the average HBO concentration of a three seconds long window that was created around the maximum HBO concentration found between post-stimulus 4.5 and 12.5 seconds interval; $Mean_{base}$ corresponds to the average HBO concentration of two seconds long pre-stimulus baseline; Std_{base} corresponds to the standard deviation of two seconds-long pre-stimulus baseline. Two analyses were performed based on HAS features: hemispheric lateralization (subject-level) and hemodynamic activity (group-level).

For hemispheric lateralization analysis, subject-level HAS values were obtained by computing the HAS parameter of each word and each channel for each subject. As a result, each subject had a 20x1 vector consisting of HAS values for Turkish words and a 10x1 vector consisting of HAS values for English words in each channel. Then, these vectors were subjected to a one-sample student t-test to identify the channels showing significant neuronal activity for each participant. Statistically significant channels were labeled as active channels. Subsequently, the Hemispheric Lateralization (HL) of each subject for English and Turkish words were calculated with the following equation:

$$HL_{sub,con} = \frac{N_{LC} - N_{RC}}{N_C} \tag{2.6}$$

where N_{LC} corresponds to the active channels found in the left hemisphere; N_{RC} corresponds to the active channels found in the right hemisphere; N_C is the total number of channels in a hemisphere (i.e., 8). This equation normalizes the HL parameter within the range of -1 to 1. Positive values correspond to left hemispheric lateralization, while negative values correspond to right hemispheric lateralization.

Vectors (14×1) were generated for Turkish and English words separately in each group with computed HL values. Next, they were subjected to a one-sample student t-test to assess whether there was significant hemispheric lateralization in a group for Turkish and English words. Lastly, hemispheric lateralization differences among the groups were investigated with a one-way ANOVA for Turkish and English words, separately.

For hemodynamic activity analysis, HAS parameter was calculated to localize the significant neuronal activity for the groups. For this analysis, block averaging was performed on 14.5 seconds long segments for each channel in each subject. Specifically, 20 segments of Turkish words were block-averaged to obtain a single 14.5 seconds-long fNIRS time-series segment for each channel and each subject. The block averaging was also performed over segments belonging to 10 English words. To summarize, each subject had a single 14.5 seconds-long segment for Turkish words and a single 14.5 seconds-long segment for English words for each channel. Then, the HAS values of these block-averaged segments were calculated separately for Turkish and English words using Eq. 2.5. As a result, each group had 14 × 16 × 2 (subject × channel ×language) matrices consisting of computed HAS values.

A one-sample student t-test was used to detect the significantly active channels in each group for English and Turkish words, separately. A channel-based paired sample student t-test was used to investigate the contrast between the Turkish and English words within the groups. Lastly, channel-based between-group comparisons were performed with one-way ANOVA for Turkish and English words, separately. All statistical analyses were conducted with MATLAB R2017B.

2.4.3 Results

The word group reported 6.57 ± 1.83 words on average, while the number group 8.79 ± 1.97 on average. Wilcoxon rank-sum test revealed a statistically significant difference between the word and number groups (Z=2.759, p=0.006).

TMT Results.

Baseline Results

Paired sample student's t-test revealed no statistically significant difference between the baseline temperatures of left and right ears in any of the groups ($t(13)=0.069$, $p=0.946$ for control group; $t(13)=-1.359$, $p=0.197$ for word group; $t(13)=0$, $p=1$ for number group). One-way ANOVA also failed to find a statistically significant difference among the groups in terms of baseline temperature difference ($F(2,39)=1.09$, $p=0.346$).

Last-Base Results

The difference between the left and right ear in terms of the temperature increase from the beginning to the end of the experiment was not statistically significant for any of the groups ($t(13)=1.467$, $p=0.166$ for control group; $t(13)=1.539$, $p=0.148$ for word group; $t(13)=1.279$, $p=0.223$ for number group). One-way ANOVA failed to find a statistically significant difference among the groups in terms of the temperature difference between left and right ears from beginning to the end of the experiment ($F(2,39)=0.47$, $p=0.628$). However, the word group had the greatest albeit non-significant difference between the left and right ears in terms of the temperature increase from the beginning to the end of the experiment (Table 2.5). Figure 2.8 shows the temperature changes of the groups throughout the experiment.

Table 2.5
Mean temperature changes from beginning to the end of the experiment in Celsius degree.

Group	L-R Difference
Control	0.078
Word	0.179
Number	0.084

Post-Pre Results

One sample student t-test revealed that the temperature increase of the left ear after a word was significantly greater than of the right ear only in the word group ($t(29)=4.202$, $p<0.001$). In the word group, the left ear temperature increased 0.025 ± 0.003 °C on average, while that of the right ear increased 0.020 ± 0.003 °C. The control group ($t(29)=1.435$, $p=0.162$) and the number group ($t(29)=1.648$, $p=0.110$) did not show statistically significant differences .

One-way ANOVA failed to find a statistically significant difference among the groups in terms of the temperature difference between ears (calculated as left minus right) after a word was heard ($F(2,87)=2.81$, $p=0.067$). However, the word group presented a non-significant greatest temperature difference calculated as left minus right ears.

Lastly, a paired sample student t-test was performed to assess whether Turkish and English words caused a temperature increase bias within the groups. However, there was no significant difference in any of the groups ($t(13)=-0.144$, $p=0.888$ for control group; $t(13)=0.37$, $p=0.717$ for word group; $t(13)=0.882$, $p=0.426$ for number group).

To sum up:

- There was no statistically significant difference among the groups at the onset of the experiment.
- The word group showed the non-significant greatest temperature increase difference between the left and right ears (calculated as left minus right) throughout the experiment (Table 2.5).
- Temperature increase difference between the left and right ears upon hearing a word caused a significant difference only in the word group. The left ear presented a significantly greater temperature increase than the right ear in the word group.
- Turkish and English words did not significantly differ in terms of temperature increase difference between the left and right ears in any of the groups.

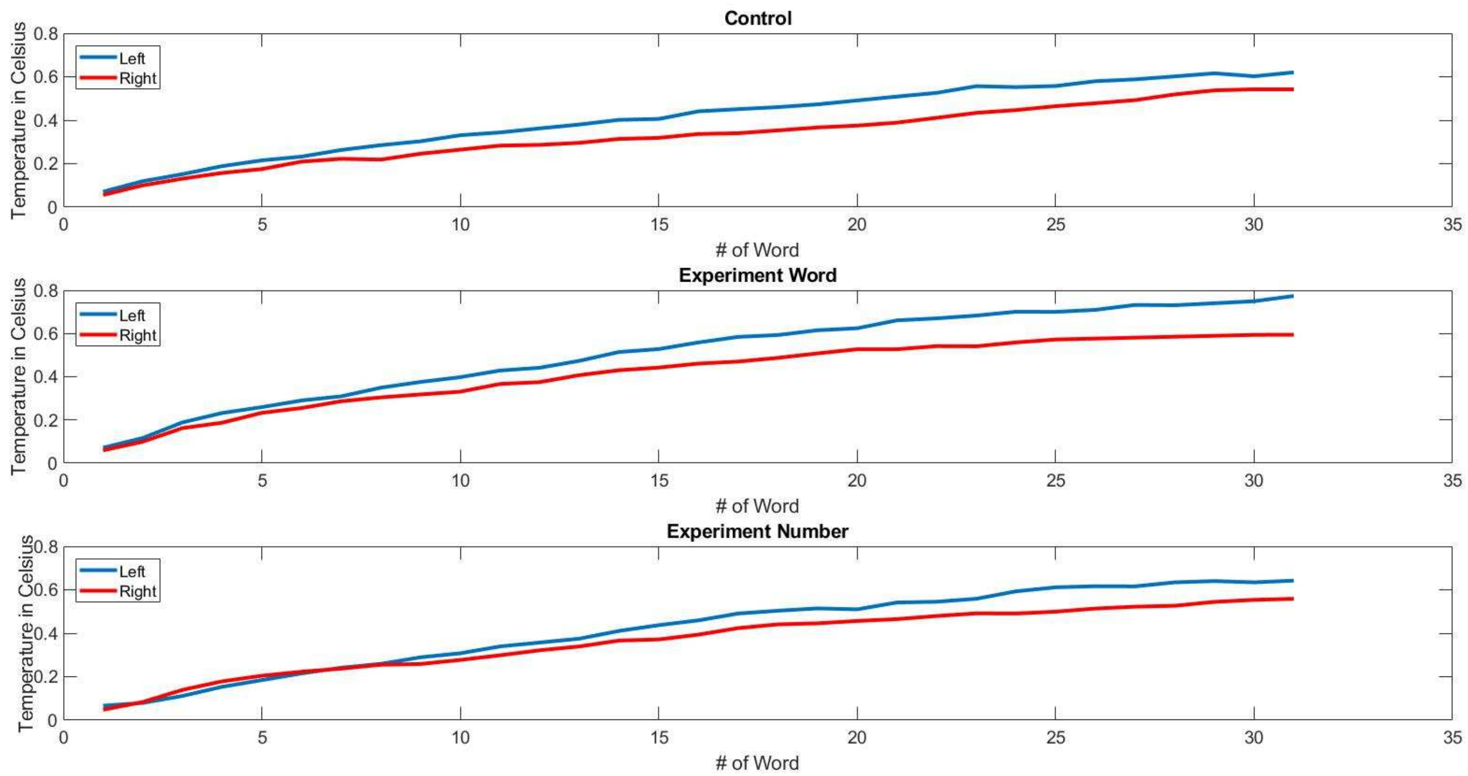

Figure 2.8 The temperature changes from baseline temperature in Control (top), Word (middle), and Number (bottom) groups during the experiment.

fNIRS Results.

One subject was excluded from fNIRS analysis in the control group and three subjects from the word group due to the high number of channels with poor signal quality. Thus, 13 subjects remained in the control group, 11 subjects in the word group, and 14 subjects in the number group for fNIRS analysis.

Hemispheric Lateralization Results

Hemispheric lateralization results can be seen in Table 2.6. One-sample student t-test revealed statistical significance only for Turkish words in the word group ($t(10)=2.235$, $p=0.049$), while other conditions did not reach a statistical significance level ($p>0.05$). Turkish words induced a significant left-lateralized activity in the word group. The paired sample student t-test showed no difference between the hemispheric lateralization scores for Turkish and English words in any of the groups ($t(12)=-0.201$, $p=0.844$ for control group; $t(10)=1.814$, $p=0.10$ for word group; $t(13)=-0.082$, $p=0.936$ for number group). One-way ANOVA analysis revealed a marginally significant difference among the hemispheric lateralization scores of the groups for Turkish words ($F(2,35)=3.21$, $p=0.052$). For the English words, one-way ANOVA failed to find a statistically significant difference among the groups ($F(2,35)=1.08$, $p=0.352$).

Table 2.6
Within-group t-test p values and mean hemispheric lateralization parameters as mean ± standard error.

	Control		**Word**		**Number**	
Groups	p	mean $\pm ste$	p	mean $\pm ste$	p	mean $\pm ste$
Turkish	0.345	0.077 ±0.078	**0.049***	0.307 ±0.137	0.547	-0.054 ±0.087
English	0.201	0.096 ±0.071	0.393	0.125 ±0.140	0.431	-0.045 ±0.055

Hemodynamic Activity Results

One sample student t-tests showed that six channels had a significant activation for Turkish words and four channels for English words in the control group ($p<0.05$). For the word group, five channels were significantly active for Turkish words and six channels for English words, while the number group had eleven significantly active channels for Turkish words and nine channels for English words ($p<0.05$). Figure 2.9 shows the anatomical locations of the significantly active channels in each group for both conditions. Heat maps were generated based on the thresholded t-statistics parameter calculated with one sample student t-test.

Channel-based neuronal activation difference between the English and Turkish words investigated with a paired sample student t-test was not statistically significant in any of the groups ($p>0.05$).

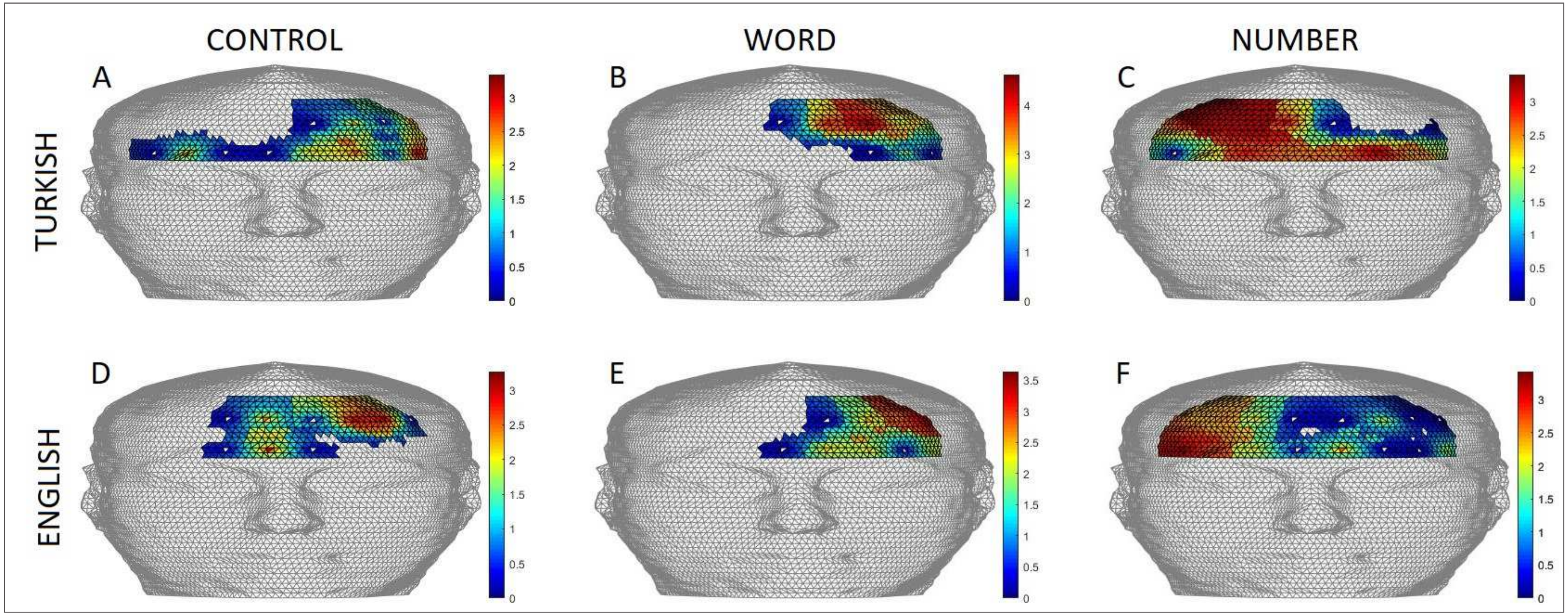

Figure 2.9 Anatomical locations of the active channels for each condition in each group.

Channel-based differences among three groups for Turkish and English words were assessed with one-way ANOVA, revealing statistically significant neuronal activation differences in channels 5 ($F(2,33)=7.27$, $p=0.002$) and 15 ($F(2,31)=7.04$, $p=0.003$) for Turkish words and channel 3 ($F(2,35)=3.89$, $p=0.030$) for English words. Channel 3 corresponds to left Brodmann Areas (BA) 10 and 46. Channel 5 also corresponds to left BA 10 and 46 with different coverage proportions, while channel 15 covers the regions of right BA 10, 45, and 46. Bonferroni corrected post-hoc t-tests showed that HAS produced by Turkish words was stronger in the word group compared to the control ($p=0.004$) and the number groups ($p=0.010$) for channel 5 (left BA 10, 46). For channel 15 (right BA 10, 45, 46), the number group presented greater HAS values than the control ($p=0.006$) and the word group ($p=0.013$). The contrast among the groups for Turkish words can be seen as thresholded heat maps in Figure 2.10.

For processing English words, only the word group had a significantly greater HAS value than the number group ($p=0.026$) for channel 3 (left BA 10, 46)(Figure 2.11).

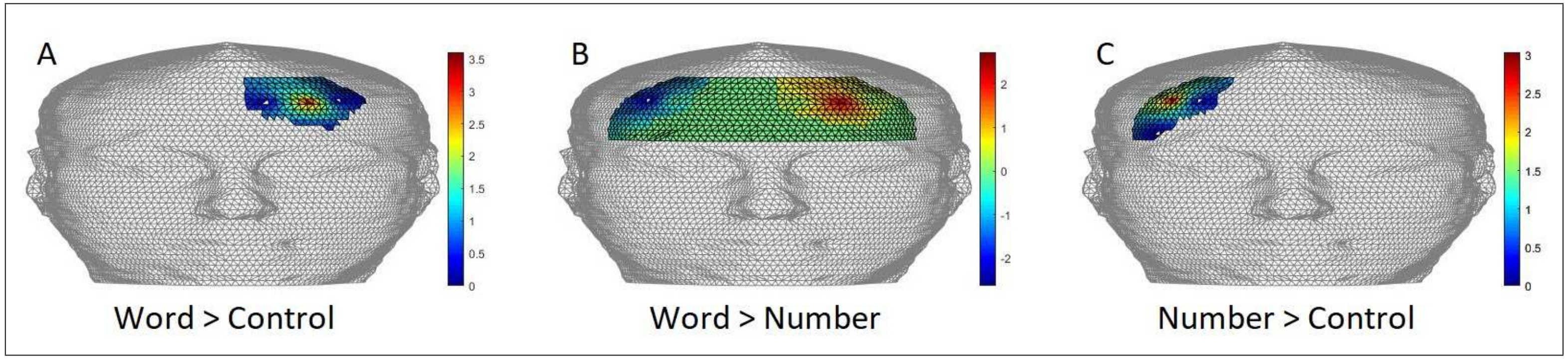

Figure 2.10 Activity strength map of processing Turkish words for A) Word>Control; B) Word>Number; C) Number>Control.

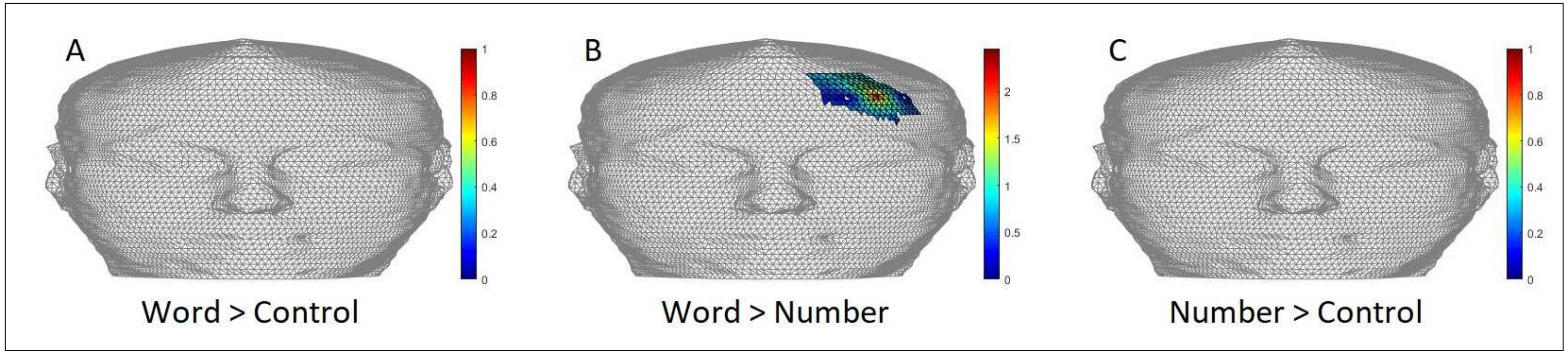

Figure 2.11 Activity strength map of processing English words for the Number>Word contrast.

2.4.4 Discussion

The control group listened to the list without any specific task; the number group had to recognize and mentally count the number of target words; while the word group had to recognize and memorize the target words. Based on the differences in the instructions, the expectation for task difficulty would be as follows: Word > Number > Control. It is known that accuracy decreases with increased task difficulty [87–89]. The number of reported items is the indicator of the task difficulty in the present experiment, thus the number of reported items was expected to decrease with increased task difficulty. The behavioral findings were in line with the initial expectation about the task difficulty.

TMT Findings.

In summary, the TMT findings of the present study have replicated the findings of the Auditory Word Level Experiment 2. Since a more detailed discussion has been provided in the previous section, a brief discussion is included below regarding the TMT findings.

The TMT part of this experiment was the replication of the previous TMT experiment with different subjects. Baseline temperature results of the present experiment also showed that there was no ear temperature bias within or between groups at the beginning of the experiment. Last-Base results also supported the view that increased neuronal activation leads to increased temperature in the ipsilateral ear. It was also demonstrated that the word group's task was cognitively the most demanding one, as they had the greatest temperature increase difference between the left and right ears. Language processing takes mainly place in the left hemisphere, and this neuronal activity was reflected in the greater temperature increase of the left ear for the word group. Failing to detect a significant within-group difference between processing English and Turkish words once again might be due to the limited technical specifications of the TMT device used in the experiments. The current device has a sampling rate of approximately 0.6 Hz and a resolution of 0.0625 °C. A TMT device with a higher sampling rate and a better resolution (e.g. 0.01 °C) can capture the significant difference between the conditions. Secondly, Turkish words may have caused a more widespread activity in the brain, while English words might have caused a greater neuronal activity within a smaller brain region. Thus, the overall blood flow towards the left hemisphere might not be different for processing English and Turkish words, resulting in no difference. Indeed, fNIRS findings of the present experiment showed that the control and number group had more active channels in processing Turkish words than English words, a case reversed in the word group (Figure 2.9). Yet, English words induced a significant activity in only one extra channel compared to Turkish words. Another confounding factor could be the event-related design of the experiment. Even though the ISI was set at 20 seconds to allow relaxation between the successive stimuli, the current experimental design might have caused a cumulative effect on temperature changes as the word group subjects were likely to repeat the words during 20 seconds long ISI, while the number group subjects were likely to keep the number of target words in their mind. Further experiments with block design can shed light on this issue and can reveal the temperature cost of processing words from the non-native language.

In summary, this experiment demonstrated that the left ear's temperature increased more than that of the right ear in all groups. Given that all groups were exposed to linguistic stimuli, TMT can be said to reflect the lateralized cognitive activity. Moreover, performing the most difficult task (word group) caused the greatest left-lateralized temperature increase.

fNIRS Findings.

Overall analysis showed that all three groups had neuronal activation in different degrees in the lateral portions of the left frontal cortex (Figure 2.9). This finding is in line with the very well-known fact that language processing in most people occurs mainly in the left hemisphere [5, 6, 111, 112]. Given that all groups were exposed to a word list, left-hemispheric activity was to be expected. The neuronal activity strength of both word and number groups was greater than that of the control group (Figure 2.9), which implies that processing words from non-native language caused greater neuronal activity even with different task requirements. Moreover, the localization of the neuronal activation in the word and number groups differed from the control group and each other (Figure 2.9). The word group was expected to recognize and then rehearse target English words throughout the experiment. Given that the left DLPFC is shown to be active during inner speech [6] and verbal working memory tasks [98,113], greater neuronal activity of the left DLPFC for the word group (Figure 2.9B and E) reflects the greater cognitive load of processing words from the non-native language. On the other hand, the number group was required only to recognize the words. The bilingual interactive plus (BIA+) model claims that interlingual homophone words activate the phonological representations in both language systems [114]. Then, these representations compete to be selected at the lexical level [61,76,115], which requires a conflict/mismatch resolution. It was demonstrated that the right DLPFC is involved in conflict monitoring and resolution in general [90,91] and inhibition of native language during non-native language processing [97]. Therefore, greater neuronal activity of the right DLPFC for the number group (Figure 2.9C and F) indicates a greater cognitive load of processing words from the non-native language. It should be noted that even simple recognition/identification of the words from non-native language was enough to induce a significant neuronal activity compared to passive listening. Even though it can be claimed that these findings are contradictory, it is possible that the different task requirements could have caused the location of the neuronal activity to be shifted. As a result, word and number groups would show dominant neuronal activity in the left and right hemispheres, respectively.

The study failed to find a within-group contrast between processing Turkish and English words in the word and number groups, even though it was hypothesized to be found. Further analysis revealed that processing English words produced a non-significant greater hemodynamic activity (i.e., HAS) than processing Turkish words in the left DLPFC for the word group, and in the right DLPFC for the number group. As stated earlier, neuronal activity was predominantly located in the left DLPFC for the word group and in the right DLPFC for the number group. Taken together, these findings support the hypothesis that processing words from a non-native language causes a greater cognitive load than processing words from a native language. It is worth mentioning that pre-experimental instructions might have prevented the within-group differences to reach statistical significance. Subjects were informed that they were going to listen to a word list composed of Turkish and English words. It has been demonstrated that pre-experimental instructions can condition the participants to reduce the activation of the non-target language and/or increase the activation of the target language [62].

To sum, the control group listened to a word list and presented a non-distinctive activation in the left hemisphere. The number group recognized the target words and presented a bilateral activation with right hemispheric lateralization, possibly due to the conflict resolution required for the identification of ambiguous words. On the other hand, the word group remembered the target words and presented a neuronal activation only in the left hemisphere, possibly due to verbal working memory and rehearsal of target words. Furthermore, words from the non-native language caused greater activation in the left and right DLPFC compared to words from the native language in the word and the number group, respectively.

For Turkish words, channel-based between-group contrasts showed that the word group had a stronger neuronal activation than the control and number groups in the left middle frontal gyrus, which covers BA 10 to a greater extent than BA46. The word group differed from the other groups in terms of rehearsal/verbal working memory processes. A meta-analysis has shown that the BA 10 is active during a variety of memory tasks that include verbal material [116]. Therefore, it is possible in the present study that significant neuronal activation in this region was associated with the rehearsal/memory-related cognitive processes. The location of the significant neuronal activation for the Number > Control and the Number > Word contrasts for Turkish words were the same and correspond to the BA 10, 45, 46 in the right hemisphere. This channel collects signals primarily from BA 46 and to a lesser extent from BA 45. It is likely that the main cognitive effort of the number group is recognition/identification of target words, thus a robust conflict/ambiguity resolution. The right DLPFC, especially BA 46, is known for playing a key role during conflict monitoring in various cognitive tasks [90, 91, 117]. Thus, stronger right DLPFC activity of the number group compared to the other two groups is likely to occur as a result of the conflict monitoring.

For English words, Word > Number contrast was found in the left DLPFC and middle frontal gyrus. The anatomical location of the active channel is closer to lateral frontal regions, thus collecting signals from BA 10 and BA 46 almost equally. Contrary to Word > Number contrast found for Turkish words, recognition of English (i.e., interlingual homophone) words was cognitively more demanding, as the subjects had to update their rehearsal list after recognizing a new English word without interrupting the repetition of their existing list of target words. Studies have demonstrated that both BA 10 [116] and BA 46 [118, 119] are associated with multitasking, suggesting that the significant activity of this region was due to the increased multitasking (i.e., recognition, inclusion into the list, repetition of the target words).

2.5 General Conclusions for the Auditory Experiments

Three auditory experiments have been carried out within the scope of the present thesis. The first one was a pilot experiment with two groups and a word list consisting of twenty Turkish (non-target) and nine English (target) words as stimuli. The other two experiments had three groups and the stimuli were a word list consisting of twenty Turkish (non-target) and ten English (target) words. The tympanic membrane temperature of participants was measured in all three experiments. In the last experiment, the prefrontal activity of the participants was also measured with fNIRS.

These experiments showed that the ear temperatures of the subjects increased throughout the task in all three experiments, favouring the increased activity - increased ear temperature view in general. Furthermore, the findings showed that stimuli consisting of words induced neuronal activity in the brain, and this activity can be captured by measuring the ear temperature. On the other hand, the temperature increase was greater in the right ear in the first experiment; a case reversed in the second and third experiments. Given that the stimuli were a word list, the neuronal activation was expected to be mainly in the left hemisphere. As stated earlier, the word list used in the first experiment was different from that of used in the subsequent experiments. In the first experiment, the word frequencies were not matched for English and Turkish words, which might have caused unexpected results. Based on the findings, it could be claimed that TMT is a reliable method for investigating a lateralized cognitive function such as language. In all three experiments, there was no significant difference between processing Turkish and English words. Two factors might have prevented this. First, the technical limitations of the TMT measurement system. Second, the event-related design of the experiment might have caused a cumulative neuronal activity effect, thus preventing to dissociate the cognitive cost of processing English words and Turkish words. It should be noted that fNIRS findings also failed to reveal a significant difference between processing Turkish and English words. Therefore, it is unlikely that the TMT system was not able to capture the processing differences of words from the native and non-native language. Hence, I suggest that the event-related design of the experiment was more likely the reason for failing to reveal processing differences. A block design experiment with similar stimuli can reveal the energy dynamics of the brain for processing words from the native and non-native language. Nevertheless, a superior thermometer can increase the quality of the recordings and results, which in turn allow assessing the thermal dynamics with better temporal resolution.

fNIRS findings of the last experiment revealed that the left hemisphere is the main source of the neuronal activity for the most difficult task (i.e., for the word group). This also supports the increased activity - increased ipsilateral temperature view. Moreover, it was shown that the location of the significant neuronal activity depends on the task. For instance, the right hemisphere was more active in the number group compared to the control and word groups. The right DLPFC was also shown to play a significant role in processing ambiguous linguistic materials.

To sum, present chapter demonstrated that processing words from non-native language causes a different ear temperature dynamics and hemodynamic activity in prefrontal cortex (in terms of both magnitude and location) than processing words from native language. The findings suggest greater cognitive demands for processing words from non-native language compared to words from native language, but further investigations with different experimental designs are required. Even though it was aimed to assess the correlation between fNIRS and TMT findings in the last experiment, it was not possible because the number of participants in fNIRS and TMT method was not even after checking the data quality. However, fNIRS and TMT results were in line with each other in terms of processing difficulty and the dominant hemisphere/ear.

3. VISUAL EXPERIMENTS

3.1 Introduction and Motivation

Auditory experiments reported in the previous chapter showed that TMT measurements can reflect the cognitive load of left-lateralized language processing. Moreover, simultaneous fNIRS findings of the simultaneous fNIRS-TMT experiment also supported the TMT findings, indicating that TMT is a valid and reliable method for assessing difficulty in auditory word processing tasks. Nevertheless, it would be better, if not necessary, to show that the TMT can reflect the lateralized brain activity in general caused by various cognitive functions.

As stated above, language processing is defined as one of the left-lateralized functioning of the human brain, while it was reported that emotion processing is a right-lateralized activity [120]. On the other hand, Alves et al. (2008) summarized that some studies have reported right hemispheric dominance for negative emotions, while left hemispheric dominance for positive emotions, favouring the valence theory of emotions [121]. Various studies have shown that visuospatial processing is also one of the right-lateralized brain functions [122–126]. Furthermore, Cherbuin and Brinkman (2004) have also shown that TMT can reflect the ongoing activity of the right hemisphere during a visuospatial task [25].

The work of Cherbuin and Brinkman (2004) can be considered sufficient to show that TMT can capture the right-lateralized brain activity as well. However, the TMT measurement system used by these authors was different from the temperature measurement system used in the present thesis. Therefore, it was decided to carry out a visual processing experiment to show that the current system can also be used in lateralization studies.

The first visual (i.e., puzzle oddball) experiment was carried out to show that

TMT can reflect the right hemisphere dominant neuronal activity as well. The second visual experiment included two tasks: mental rotation and relative clause processing. In the second experiment, the neural activity of the prefrontal cortex was assessed with fNIRS. It was aimed to show that language processing and visual processing cause neuronal activation in different brain regions.

The pertinent literature was provided for each experiment in the subsections below. Furthermore, the experimental design, aims, and hypotheses for each experiment were also stated below.

3.2 Chapter Overview

This chapter covers the following experiments:

- **TMT Experiment:** Thirteen subjects participated in the experiment. The subjects were asked to discriminate ten target puzzle pieces from twenty non-target puzzle pieces. Tympanic membrane temperatures of both ears were continuously recorded during the experiment. This study was presented as a poster during the 2018 National Neuroscience Congress.

- **fNIRS Experiment:** Fourteen subjects participated in two tasks in a counterbalanced design. fNIRS recordings from frontal regions were collected during both tasks.

  Mental Rotation: This experiment required mentally rotating the puzzle pieces to fit them into a puzzle template. This study was published as a journal paper ('Functional Near-Infrared Spectroscopy Indicates That Asymmetric Right Hemispheric Activation in Mental Rotation of a Jigsaw Puzzle Decreases With Task Difficulty') in *Frontiers in Human Neuroscience*.

  Relative Clause: This experiment required subjects to answer questions about ten-word long sentences that contained either object relative clause or subject relative clause.

A detailed explanation of methods, analysis, and results is provided in the relevant subsections.

3.3 Visual TMT Experiment

3.3.1 Background and Introduction

Various studies have demonstrated that visuospatial processing is one of the cognitive functions that induce right-lateralized neuronal activation. For instance, mental rotation studies have shown that the right hemisphere is the main locus of neuronal activity [127–130]. Moreover, Cherbuin and Brinkman (2004) reported that mentally manipulating unfolded cubes causes significant temperature changes in the right ear, which was interpreted as right hemispheric activation by the authors [25]. Processing faces was also associated with right hemispheric activity [131, 132]. Furthermore, Stephan et al. (2003) found that the right hemisphere is active during a visuospatial decision task, in which the subjects were asked to locate the position of a target [133].

In the auditory experiments of the present thesis, subjects were asked to remember or count the target (i.e., English) words from a mixed word list. Subjects had to discriminate the target stimuli from non-target stimuli in these experiments, which required a word (i.e., target) recognition or identification. In the first visual experiment, it was aimed to carry out a similar experiment. To that end, a simple visual recognition experiment was designed.

The work of Stephan et al. (2003) can be considered as an example of a visual recognition experiment. The authors used the well-known oddball paradigm in their study. The oddball paradigm is a well-known auditory or visual experimental design in which infrequent, different (i.e., target) stimuli are presented to subjects within a larger set of frequent, expected (i.e., non-target) stimuli. It has been used in visual discrimination and target detection researches as well as attention-related researches. Oddball paradigms have been studied with various imaging modalities such as EEG

[122, 134, 135], fMRI [134, 136], fNIRS [135, 137]. Moreover, many studies show that visual oddball paradigms induce a strong right hemisphere activity [138–140]. As a further example, Kirino et al. (2000) reported that subjects demonstrated a greater right middle frontal gyrus activity for targets compared to non-targets in a visual oddball paradigm [141]. The authors have also reported that the right hemispheric neuronal activation was present, even after the target and non-target stimuli were interchanged. An fNIRS study also showed that the hemodynamic activity of the right hemisphere is greater during oddball tasks and that HBO concentrations measured from the right prefrontal cortex change with the task difficulty [135].

3.3.2 Hypotheses

Auditory experiments showed that TMT could dissociate the activity of the left and right hemispheres in a language processing task that induced left hemisphere dominant neuronal and thermal activity. It is important to show that TMT is not limited only to language processing tasks and can reflect the right hemisphere dominant activity. Therefore, it was aimed to assess with TMT the cognitive load and energy dynamics of a visual processing task, which was expected to induce right dominant activity. To that end, a novel, visual oddball paradigm was designed with puzzle pieces that was refractory to verbalization. The participants were asked to identify the target pieces while their ear temperature was measured continuously. For this experiment, it was hypothesized that the temperature increase in the right ear should exceed that of the left ear. Moreover, target puzzle pieces were expected to cause a greater temperature increase than non-target puzzle pieces.

3.3.3 Materials and Method

Thirteen postgraduate students from the Institute of Biomedical Engineering of Boğazici University were recruited for the study. There were eight females and five males. The mean age was 27.08 ± 2.43, and one subject was left-handed. All subjects were informed before the experiment and gave written consent. The study was approved by the local ethical committee, the Human Research Ethical Committee of Boğazici University.

The TMT measurement device (Figure 2.1) used in Section 2.3.2 Auditory Word Level Experiment 1, was also utilized in this experiment to record the ear temperature of the subjects.

In the experiment, subjects were asked to discriminate the two types of visually presented puzzle pieces: target and non-target. Target puzzle pieces had a dot within themselves, while non-target puzzle pieces did not (Figure 3.1). The stimuli consisted of randomly ordered twenty non-target and ten target puzzle pieces with a 20 seconds interval between each puzzle piece. The experiment was designed with PsychoPy 1.85 software [142].

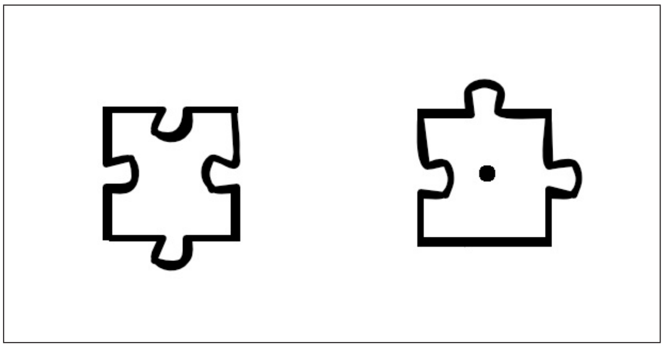

Figure 3.1 Examples of non-target and target puzzle pieces. Non-target on the left and target on the right, respectively.

Experiments were carried out in a dimly lit, silent room. The ambient temperature was set within the range of 20-25° Celsius via an air conditioner system. The stimuli were presented on a 24-inch computer screen. All visual cues and stimuli were presented at the center of the screen. After the acquisition of demographics, the experimental protocol was explained in detail to each subject. Subjects were instructed to report the number of target puzzle pieces from the stimuli list at the end of the experiment.

Subjects were asked to sit in a chair positioned in front of a computer screen so that the distance from the computer screen to the subject's eyes was 50 cm. The sensors were placed in both ear canals of subjects following the instructions. Subjects were then told to sit silently and motionless as much as possible to allow for sensors to reach an equilibrium temperature with ear canals. Simultaneously stabilized temperature recordings of both ears for at least twenty seconds was required for reaching the equilibrium [34] to start the experiment. Once the equilibrium was achieved, the subject was informed that the experiment had started, and simultaneously the experiment was started on the Psychopy software. A plus sign was presented as a fixation point for 300 ms before each stimulus to briefly warn the subjects. Subsequently, a randomly chosen target or non-target puzzle piece was shown on the computer screen for 500 ms, followed by a white noise image presentation for 500 ms to eliminate the after-image effects. The interstimulus interval was 20 seconds. The complete experimental procedure can be seen in Figure 3.2. After the experiment, the subjects were asked to report the number of target pieces they saw.

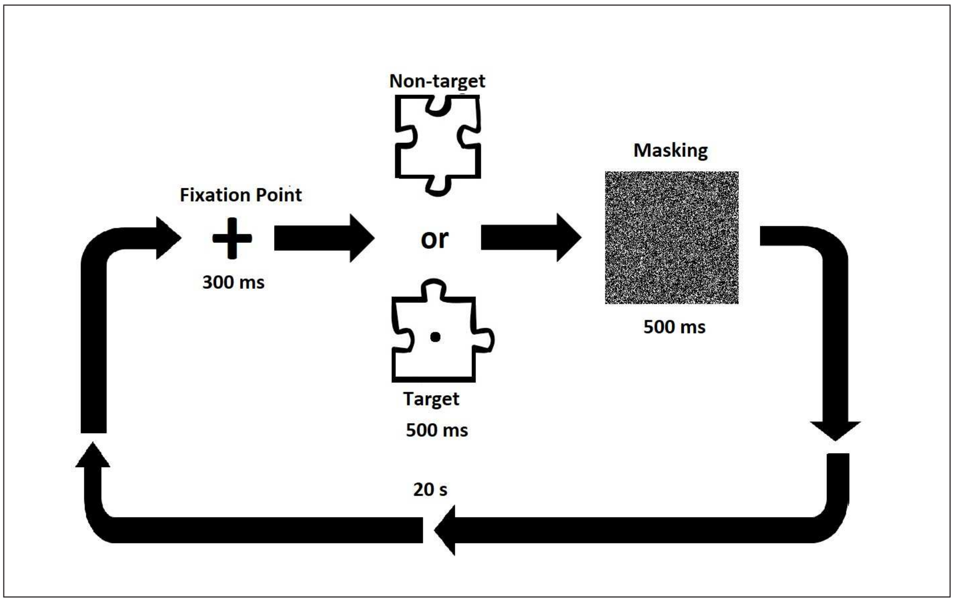

Figure 3.2 The complete experimental procedure.

Analysis.

Only within-group analyses were performed in this experiment. Data sets were created by using the relevant equations defined in Section 2.3.2 Word Level Auditory Experiment 1 and Section 2.3.3 Word Level Auditory Experiment 2. The Baseline data set was created by using Eq. 2.1, while Eq. 2.2, 2.3, and 2.4 were used to prepare the Last-Base data set. Post-Pre data set was created for each puzzle piece with the same steps explained in the Analysis part of Section 2.3.3 Word Level Auditory Experiment 2. Data parsing of the present experiment can be seen in Figure 3.3.

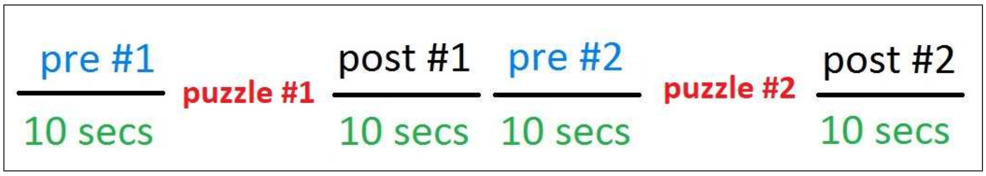

Figure 3.3 Data parsing for the *Post-Pre* data set of Puzzle experiment.

To sum up, the following data sets were created for analysis:

- ***Baseline***: 13×1 vector consisting of the temperature difference between the left and the right ear at the onset of the experiment.
- ***Last-Base***: 13×1 vector consisting of the difference between the left and right ear's temperature increase (or decrease) from onset to the end of the experiment.
- ***Post-Pre***: 30×1 matrix consisting of the average temperature difference between the left and right ears caused by each puzzle piece.

One sample student t-test was used for the within-group analysis of *Baseline*, *Last-Base*, and *Post-Pre* data sets. All statistical analyses were performed in MATLAB R2017.

3.3.4 Results

The average number of target pieces reported by the subjects was 9.77 ± 0.60.

Baseline Results.

Paired sample student t-test revealed no statistically significant difference between the ear temperatures at the beginning of the experiment ($t(12)=1.397$, $p=0.188$).

Last-Base Results.

The right ear's temperature increased more than the left ear's temperature from the beginning to the end of the experiment (Figure 3.4). Paired sample student t-test revealed that the temperature increase in the right ear, from onset to the end of the experiment, was significantly higher than the temperature increase in the left hemisphere ($t(12)=3.031$, $p=0.010$). The mean temperature increase for the left ear was 0.27 ± 0.13 °C, while it was 0.50 ± 0.08 °C for the right ear (Table 3.1).

Table 3.1
Mean temperature changes from beginning to the end of the experiment in Celsius degree. * denotes $p<0.05$.

Left Ear	Right Ear	R-L Difference
0.269	0.503	0.234*

PostPre Results.

One sample student t-test revealed a statistically significant difference between the left and right ears' temperature increase after a stimulus ($t(29)=4.091$, $p<0.01$). The mean temperature increase after a stimulus was 0.006 ± 0.001 °C and 0.010 ± 0.001 °C for the left and right ears, respectively. The temperature increase difference

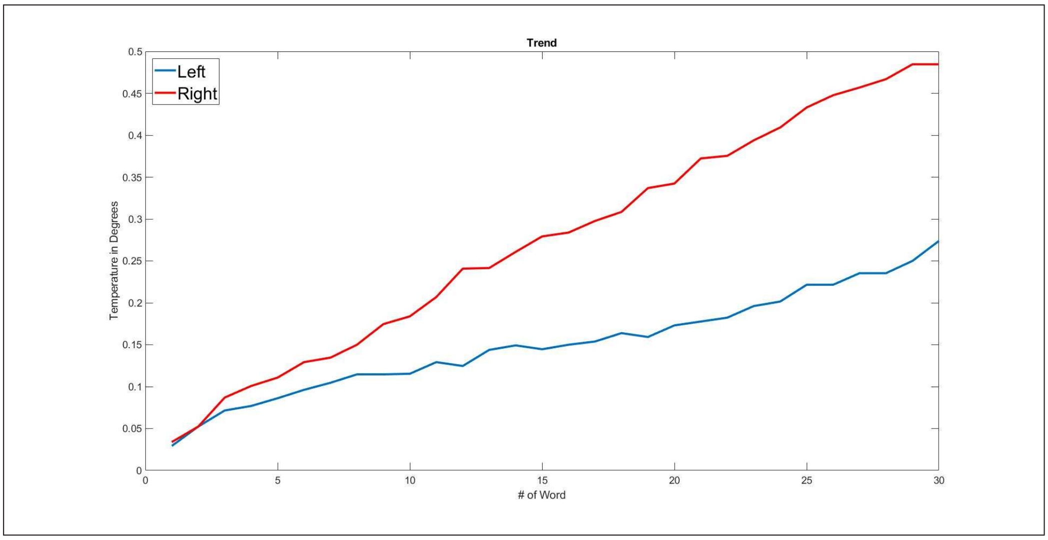

Figure 3.4 Temperature change of the left and right ears' during the experiment.

between the ears was calculated for target and non-target pieces independently. Paired sample student t-test showed no statistically significant difference between target and non-target puzzle pieces ($t(12)=0.258$, $p=0.8$). Albeit non-significant, the greatest temperature increase was in the right ear for processing target pieces.

To sum up:

- There was no ear temperature bias at the beginning of the experiment.
- Temperature increase of right ear significantly exceeded the temperature increase of left ear throughout the experiment.
- Processing the stimuli caused a significantly greater temperature increase in the right ear compared to the left ear.
- Despite the differences were not statistically significant, the highest temperature increase was in the right ear for target pieces, while the lowest temperature increase was in the left ear for non-target pieces.

3.3.5 Discussion

In the present experiment, it was aimed to show that TMT is not limited to left-lateralized language processing tasks and can also be used to assess the right-lateralized brain activity. To that end, tympanic membrane temperatures of the subjects were recorded during a simple visual discrimination/recognition task.

The average number of reported target items shows that the participants followed the instructions and actively participated in the experiment. Moreover, none of the subjects reported less than nine items, which indicates a high accuracy.

Baseline results showed that the subjects did not have any ear temperature bias at the beginning of the experiment. Therefore, it can be claimed that any further temperature differences were the result of the task. Last-Base results once again showed that the increased neuronal activity causes an increase in the ipsilateral ear temperature. The pre-experimental expectation in this experiment was to see a greater temperature increase in the right ear, as it was shown that visual processing occurs mainly in the right hemisphere [25, 130, 133]. The fact that the temperature increase of the right ear was significantly greater than the left ear throughout the experiment is in line with the initial expectation. Thus, the findings showed that processing visual stimuli caused a significant neuronal activation in the right hemisphere. Moreover, PostPre results also supported that the main neuronal processing occurred in the right hemisphere. Lastly, the findings failed to reveal a significant difference between processing target and non-target pieces. This finding was in line with the auditory experiments, in which the difference between processing words from native and non-native language was not significant. Once again, the event-related experimental design might have caused a cumulative effect in the temperature changes, which makes it impossible to dissociate the processing cost of a target from a non-target piece. The other possible reason could be that the task was not difficult enough to produce a significant temperature change between target and non-target pieces. Despite being not statistically significant, the highest temperature increase was in the right ear for processing target pieces, while the least temperature increase was in the left ear for processing non-target pieces.

These findings together indicated that visual processing mainly occurred in the right hemisphere and distinguishing target pieces from non-target pieces caused a greater neuronal activity in the right hemisphere and temperature increase in the right ear.

Taken together with the auditory experiments' results, the present experiment showed that TMT is a reliable and valid method for assessing both left and right-lateralized brain activity. The fact that the greatest temperature increase, despite being non-significant, was found in the right ear for target pieces suggests that a different experimental design can reveal the processing difficulty difference between the target and non-target pieces with TMT.

3.4 fNIRS Experiment

In previous TMT experiments, it was found that language processing and visual processing tasks distinctively activate left and right hemispheres, respectively. The dominant activity of a hemisphere was found to be reflected in the ipsilateral ear's temperature dynamics. The last auditory word processing experiments included fNIRS recordings to support the findings of TMT findings. However, prefrontal hemodynamics were not assessed in the first visual processing experiment (i.e., puzzle oddball). Therefore, it was decided to perform another experiment. The aim of this experiment was to show that language and visual processing differs from each other in terms of the location and the magnitude of the neuronal activity. The other aim of this experiment was to provide a neuroimaging basis for future TMT-lateralization studies.

In this experiment, fourteen subjects performed two cognitive tasks: mental rotation and relative clause processing in a counterbalanced design. The participants, the fNIRS device, and the experimental design were the same for the following two experiments. Therefore, a common material method and data analysis sections were given in the beginning. Literature review, material and method, results, and discussion sections are provided for each experiment separately.

3.4.1 Common Material and Method

Fourteen healthy volunteer subjects participated in the study. There were eight females and six males. The mean age was 28.07 ± 3.20, and three subjects were left-handed. The subjects participated in two experiments: mental rotation and the relative clause. The experiments were counterbalanced. Half of the subjects participated in the relative clause experiment first, while the other half started with the mental rotation experiment. There was a 15 minutes long break between the experiments. All subjects were informed before the experiment and gave written consent. The study was approved by the local ethical committee, the Human Research Ethical Committee of Boğazici University.

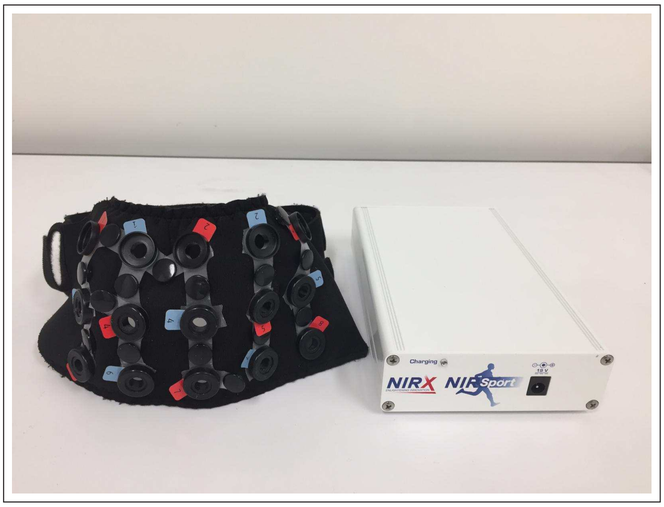

Figure 3.5 NIRX NIRSport fNIRS device and headband.

22-channel NIRSport system (NIRx Medical Technologies, LLC, Berlin, Germany) was used to collect the hemodynamic activity from the frontal cortex of the subjects (Figure 3.5). The system had eight light sources (wavelengths of 760 and 850 nm) and seven detectors. The sampling rate was 7.8125 Hz, and the source-detector distance was 3 cm. Approximate channel locations were projected onto a standard brain template by using the NIRS_SPM toolbox and can be seen in Figure 3.6 [143–145].

Experiments were carried out in a dimly lit, silent room. The ambient temperature was set within the range of 20-25° Celsius via an air conditioner system. Subjects

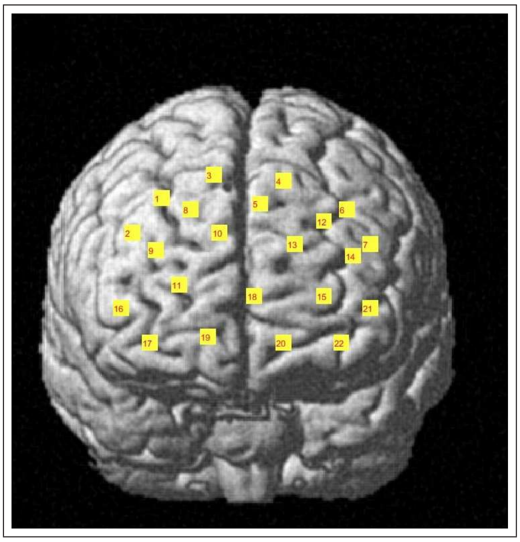

Figure 3.6 Projected channel locations projected onto a standard brain template in MNI space.

sat in front of a computer screen with a 50 cm eye-to-screen distance. All experimental cues and stimuli were presented on a 24-inch computer monitor. After the acquisition of demographics, each subject was informed about the experimental protocol.

Common Data Analysis.

For the behavioral analysis, accuracy rates were calculated by dividing the number of correct answers by the total number of trials. The reaction times were also recorded in both experiments. For the trials in which the subjects did not give a keyboard response within a 3 seconds long response window, the reaction time was set at the maximum value of 3 seconds in both experiments.

The recordings were preprocessed with a combination of nirsLAB (a free analysis software of NIRSPort system), Homer2, and custom-made MATLAB scripts before the analysis. The raw intensities were visually inspected as a first step. Then, the channels with a low signal quality were eliminated by employing the CV method. The preprocessing pipeline explained under the *Analysis* part in Section 2.4 was also used for this data set: 1. Converting optical intensities into optical densities; 2. Detecting and removing motion artifacts with PCA filtering; 3. Removing physiological noises with

Butterworth bandpass filter; 4. Converting de-noised optical densities into hemoglobin concentrations.

3.4.2 Mental Rotation Experiment

Background and Introduction.

Mental rotation is a cognitive ability that allows humans to mentally rotate objects without physical manipulation. The first mental rotation study was carried out by Shepard and Metzler [146] and new variants have been developed and used in numerous studies since then. With the development of novel imaging techniques, the mental rotation has been studied with fMRI [147, 148], fNIRS [149], and PET [150], together with the traditional behavioral metrics that have been used in earlier studies [146, 151]. Neuroimaging studies have produced controversial results for mental rotation. Most of the studies demonstrated a right hemisphere dominant activity during mental rotation [127–129]. For instance, Hugdahl et al. (2006) have reported greater neuronal activity especially in the right frontal regions in a mental rotation task based on three dimensional shapes [152]. Moreover, Suchan et al. (2002) have investigated the memory load and rotation effect during a mental rotation task in a series of experiments [153]. The authors have claimed that the activity of the right dorsolateral prefrontal cortex was associated with the active manipulation of the visual stimuli and the monitoring of the information. However, other studies have found neuronal activity in the left hemisphere [154,155] or even bilateral activation [149,152,156,157]. It was also claimed that various factors could have lead to contradictory results. For example, Mehta and Newcombie (1991) showed that mentally rotating 3D shapes was affected by left hemispheric lesions [154]. On the other hand, other studies have found that lesions in the right hemisphere affect the performance during the mental rotation of 2D shapes [127, 158]. Therefore, it was claimed that increased task difficulty causes the left hemisphere to show a greater neuronal contribution to mental rotation. On the other hand, Corballis (1997) proposed that the rotation strategy and employment of the other cognitive abilities might cause increased left-hemispheric activity [159]. He has suggested that participants rotate simpler shapes in a holistic fashion, while more complex shapes in a relatively piecemeal fashion by focusing on the local features of the shapes. Furthermore, he has also suggested that the participants can use other cognitive abilities such as verbalization during more complex scenarios.

Hypotheses

The previous puzzle experiment showed that target pieces induced a greater but non-significant temperature increase in the right ear. As stated above, there is a possibility that distinguishing dotted puzzle pieces from empty puzzle pieces might not be difficult enough. Therefore, it was aimed to develop a novel visual processing experiment with different levels of difficulty to investigate the contribution of the left and right prefrontal cortex to perform a mental rotation based visual processing task. Furthermore, this experiment would allow comparing and reinterpreting the findings of the previous visual processing experiment. The last aim of the present experiment was to establish a basis for future visual processing TMT studies. The main hypothesis was to find a significant hemodynamic activity in the right hemisphere. Moreover, it was hypothesized that the neuronal activity particularly in the right hemisphere should be increased with task difficulty.

Material and Method.

In this experiment, subjects were asked to decide whether a jigsaw puzzle piece could fit into a puzzle template while their prefrontal heodynamic activity was measured with fNIRS. There were 24 puzzle piece-template pairs (i.e., trials) in the experiment. Six trials constituted the perfect match (PM) condition, in which puzzle pieces could fit into the template without requiring manipulation. The other six trials required mentally rotating the puzzle pieces to fit them into the template and labeled as the Match (M) condition. Lastly, the remaining twelve trials formed the non-match (NM) condition in which the puzzle pieces could not fit into the template even with manipulation. Therefore, twelve Match trials formed the congruent condition and required a 'Yes' answer, while twelve Non-Match trials formed the incongruent condition and required a 'No' answer. An example from each condition can be seen in Figure 3.7. The trials were randomly presented to the subjects.

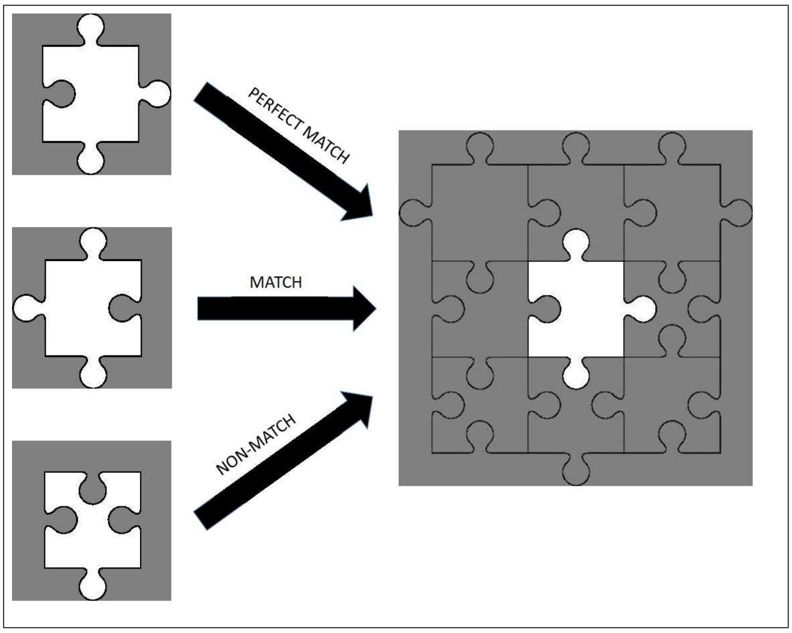

Figure 3.7 Examples of Perfect Match, Match, and Non-Match trials.

The experiment began with a baseline fNIRS recording for 30 seconds. Then, the subjects had to press the 'Space' key to start the experiment. A plus ('+') sign was presented at the center of the screen for 500 ms before presenting each puzzle piece. The puzzle piece was shown on the screen for 500 ms, after which a white-noise masking image was presented for 750 ms to eliminate the after-image effects of the puzzle piece. Next, the puzzle template was presented for 3 seconds on the screen during which the subject was expected to answer by pressing 's' (i.e., 'Yes') or 'k' (i.e., 'No') keys on the keyboard. Lastly, a white-noise masking image was shown once again for 750 ms to eliminate the after-image effect of the template. The total duration of a single trial was 5.5 seconds. The inter-stimulus interval was randomly set for each trial from the range of 9 - 12 seconds to prevent the subjects' anticipation (Figure 3.8). PsychoPy 3.0.6 [142] was used to design the experiment and record the reaction times and accuracy rates. The continuous fNIRS recording was performed during the experiment.

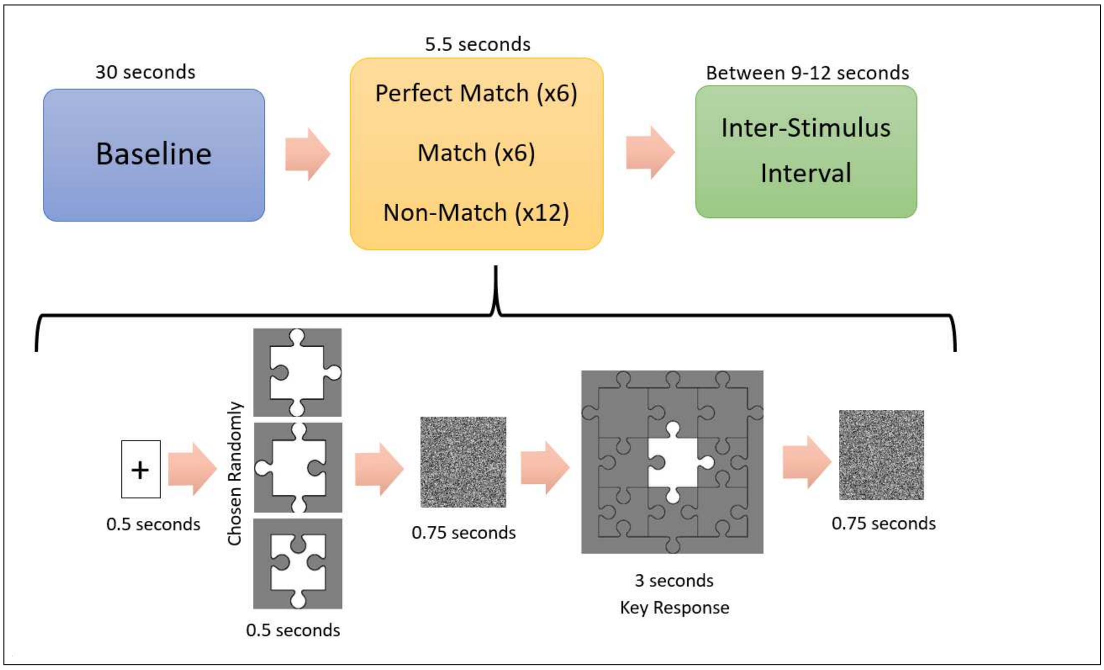

Figure 3.8 Mental Rotation Experimental Procedure.

Data Analysis

For each subject, average accuracy and reaction times were calculated in each condition. One-way repeated measure ANOVA was used for analyzing the accuracy and reaction time results.

Fourteen-second long segments, spanning from 2 seconds pre-stimulus baseline interval to 12 s long duration after the stimulus, were created for each trial. fNIRS recording system used in this experiment was different from that used in the word processing experiment. Moreover, these devices have different sampling rates which caused using different post-stimulus activity windows (i.e., 12,5 seconds and 12 seconds) in the analysis. Subsequently, each segment was detrended and labeled as a perfect match, match, or non-match condition trial.

The significantly active brain regions of a subject in each condition were localized as follows: 1. HAS parameter of each trial (6 for PM and M conditions; 12 for NM condition) was computed separately for each condition and channel with Eq. 2.5. 2. One sample student t-tests were performed on the HAS values belonging to each condition and channel separately. 3. Statistically significant channels ($p < 0.05$) were labeled as active channels.

Hemispheric lateralization was calculated by using an updated version of Eq. 2.6. The normalization was performed with $N_C = 10$, as there were ten channels in each hemisphere for this probe. The other change was replacing the numerator part of the equation, $N_{LC} - N_{RC}$, with the $N_{RC} - N_{LC}$. Therefore, positive $HL_{sub,con}$ values corresponded to right hemispheric dominance, while the negative values corresponded to the left hemispheric dominance. Hemispheric lateralization was computed in each condition for each subject. 14×1 vectors were created for each condition with the computed hemispheric lateralization values. One-sample student's t-test was used to assess the lateralization of the conditions. One-way ANOVA was employed to assess the hemispheric lateralization difference among the conditions.

To localize the significant brain activity, the group-level HAS parameter was computed with the following steps: 1. The labeled segments (PM, M, or NM) were block averaged to obtain a single 14 seconds long segment for each channel and subject (i.e., there would be three averaged segments, each belonging to one condition, for each channel of a subject). 2. HAS of the block averaged segments were calculated for each condition in a subject with Eq. 2.5. 3. 14×3 matrices (subject×condition) were created with the computed HAS values for each channel.

A channel-based one-sample student t-test was performed on group-level HAS matrices to find the significantly active channels for each condition. Moreover, channel-based one-way repeated measure ANOVA was performed with the condition as the main effect to investigate the contrasts among conditions. Pairwise comparisons were performed with Bonferroni corrected post-hoc t-tests for the following contrasts: Match > Perfect Match, Non-Match > Perfect Match, and Non-Match > Match.

Channels were not included as a main factor in ANOVA analyses, as it was suggested that each fNIRS channel collects signal from different brain regions with different optical properties, which can lead a systemic bias in the results [160, 161].

All statistical analyses were conducted with IBM SPSS Statistics 2015 and MATLAB R2017B.

Results.

Accuracy and the reaction time results can be seen in Table 3.2. One-way repeated measure ANOVA revealed a statistically significant difference among conditions (F(2,39)=4.931, p=0.015) in terms of reaction times. Bonferroni corrected post-hoc analysis showed that answering match condition trials required a significantly longer time than perfect match trials (p=0.02). The accuracy data did not show a significant difference among conditions in one-way repeated measure ANOVA (F(2,39)=0.236, p=0.791).

Table 3.2
Behavioral data of Mental Rotation experiment.

	Perfect Match	**Match**	**Non-match**	**Average**
Accuracy	0.952 ± 0.102	0.941 ± 0.106	0.964 ± 0.063	0.952 ± 0.090
Reaction time (s)	1.146 ± 0.327	1.394 ± 0.486	1.210 ± 0.287	1.250 ± 0.382

Hemispheric lateralization of each subject for each condition can be seen in Table 3.3. One sample student t-test revealed significant right hemispheric dominance only for the perfect match condition (t(13)=2.5, p=0.027). Although the other two conditions showed a slight right hemispheric dominance, this did not reach a statistically significant level. One-way repeated measure ANOVA failed to find a statistically significant difference among conditions in terms of hemispheric lateralization (F(2,39)=0.22, p=0.806).

Table 3.3
Hemispheric lateralization for each condition. * denotes p<0.05.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	**mean ± std**
PM	0.2	-0.1	0	0	0	0	0	0.1	0	0.1	0.1	0.3	0.1	0.2	0.071 ± 0.029*
M	0	0	0.3	0	0.3	-0.2	0	0	0	0.4	-0.1	-0.2	-0.2	-0.1	0.029 ± 0.049
NM	-0.1	-0.2	0.4	-0.3	0.3	0.1	0.1	0.2	0.3	-0.1	-0.1	0.2	0.1	-0.4	0.036 ± 0.064

Channel-based one sample student t-test of group-level HAS parameters revealed different activity patterns for each condition. As can be seen from Figure 3.9, the perfect match group showed a predominantly right hemispheric activity, while match and non-match conditions presented a bilateral activity in frontal regions.

One-way repeated measure ANOVA revealed that Channel 9 ($F(2,26)=6.500$, $p=0.025$) and Channel 14 ($F(2,24)=4.059$, $p=0.039$) were significantly active. Bonferroni corrected post-hoc t-tests showed that the non-match condition had a significantly stronger activity than the perfect match ($p=0.004$) and match ($p=0.005$) conditions in channel 9. For channel 14, there was a statistically significant difference between match and perfect match conditions ($p=0.014$). The location of channel 9 corresponds to the right dorsolateral prefrontal cortex (DLPFC), while channel 14 corresponds to the left DLPFC. The pairwise contrast between conditions can be seen in Figure 3.10.

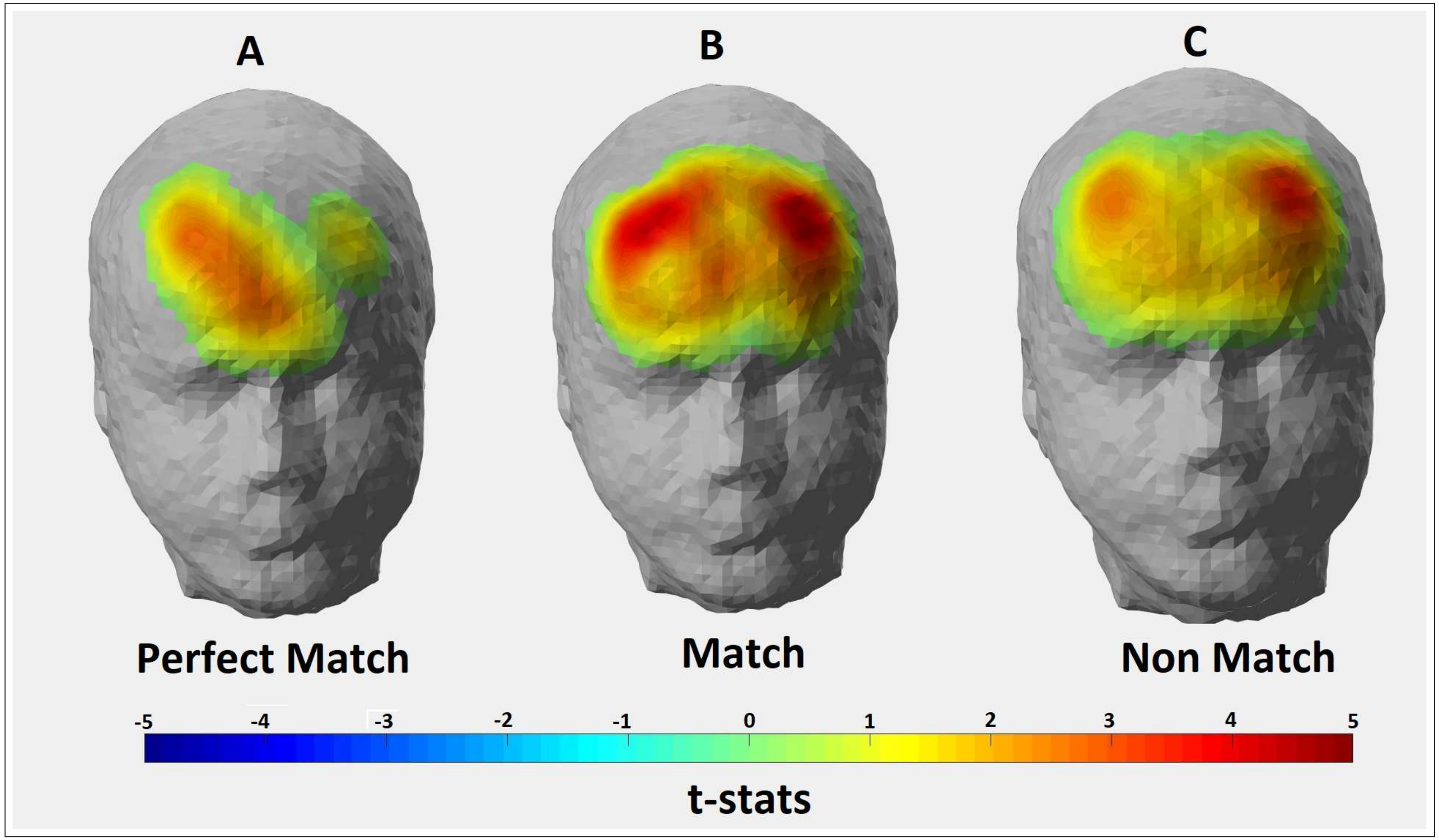

Figure 3.9 Group-level neuronal activities in Mental Rotation experiment.

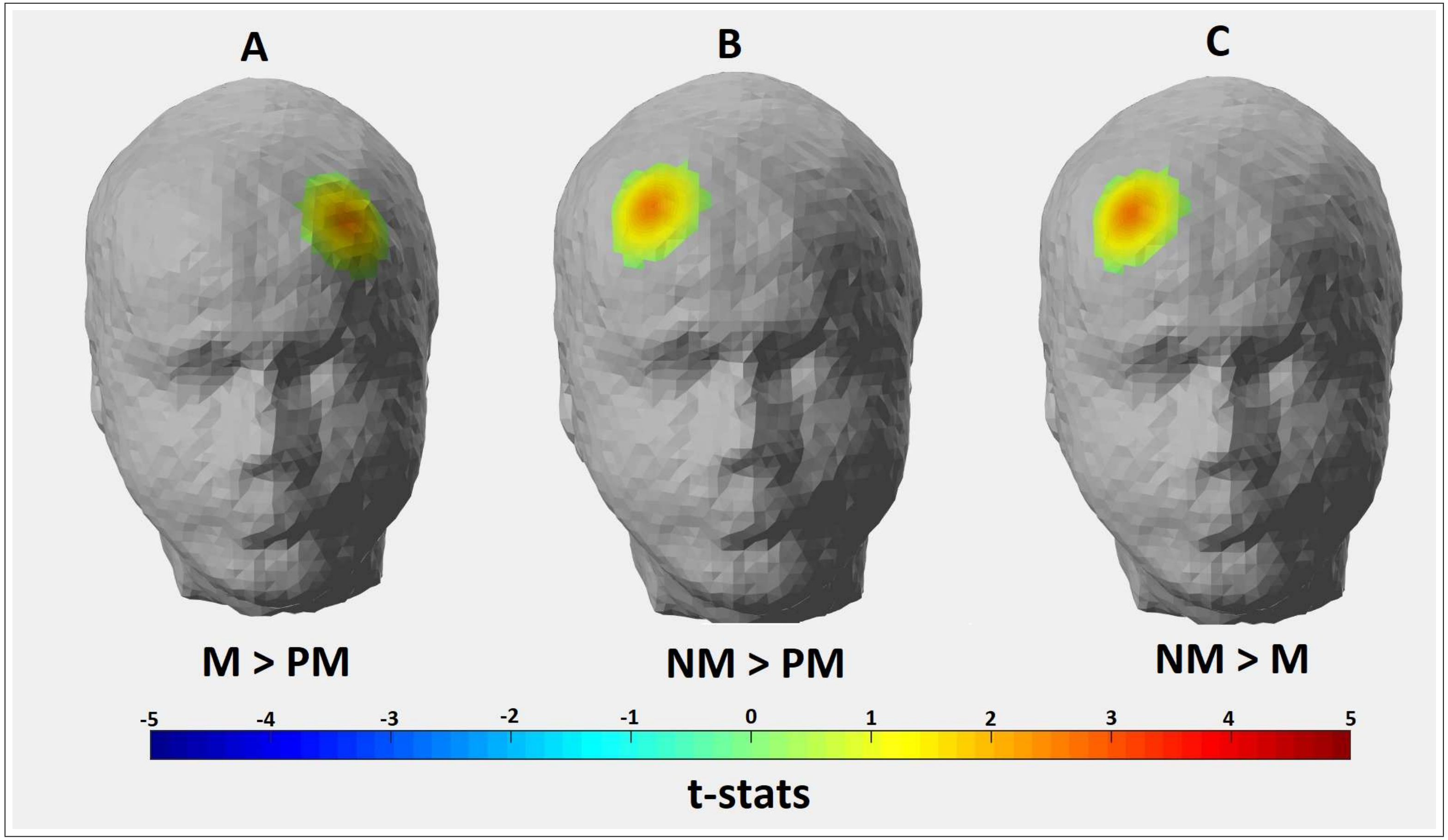

Figure 3.10 Group-level pairwise contrast activities of the conditions in Mental Rotation experiment.

Discussion.

The subjects of the present visual processing experiment also participated in a sentence processing experiment reported in the following section. The motivation for these experiments was to show that visual processing and language processing cause distinct neuronal activity in the brain. Furthermore, it was aimed to investigate how task difficulty modulates the location and the magnitude of the neural activity in the prefrontal cortex. The other aim was to provide a neuroimaging basis for future TMT experiments that can be carried out with a novel TMT device developed within the scope of this thesis. In summary, the mental rotation based visual processing task caused a significant activity especially in the right DLPFC of the subjects regardless of the task difficulty. Moreover, it was found that increased task difficulty induced neuronal activity in the left DLPFC. The findings of the present experiment supported the previous visual processing experiment, in which the greatest temperature increase was found in the right ear for discriminating target puzzle pieces from non-target puzzle pieces (see Section 3.3 Visual TMT Experiment).

Shepard and Metzler (1971) have claimed that a longer reaction time indicates a greater task difficulty [146]. Thus, based on the reaction time results (Table 3.2), the Match condition was the most difficult task, while the Perfect Match was the least difficult task in the present design. Subjects did not need to manipulate or rotate the puzzle pieces in the Perfect Match condition. On the other hand, Match and Non-Match conditions required manipulating the pieces to arrive at a judgment, which was likely to cause other cognitive processes such as mental rotation, verbalization, processing local features of stimuli to be employed. Subjects' accuracy rates were very high (Table 3.2), indicating that they successfully performed the tasks. Even though the difference among the groups was not significant, subjects' accuracy rate was lower in the Match condition compared to the other two conditions, which supports the reaction time findings, indicating that the Match condition was the most difficult task.

Group-level activity analysis showed that the right DLPFC was active in all three conditions. This finding is in line with numerous mental rotation studies [150,152, 158, 159]. Subjects had to keep the puzzle pieces' shapes in their memory before making a decision during the presentation of the template in all three conditions. Therefore, it can be claimed that the visual working memory was crucial for performing these tasks. Numerous studies have found that the right DLPFC is involved in visual working memory [162–164], which was also supported by the present experiment. Delayed match-to-sample (DMTS) tasks are widely used in cognitive neuroscience, in which the subjects were asked to evaluate the similarity of a stimulus with a target object. Daniel et al. (2016) have stated that DMTS tasks have three core phases (i.e., cue, delay, and response) [164]. The authors added that only maintaining the relevant information in the working memory can be sufficient to perform tasks similar to perfect match trials of the present experiment. Therefore, relying solely on the right hemisphere could be sufficient to succeed in perfect match trials. On the other hand, Match and Non-Match conditions demonstrated a left-hemispheric activity, in addition to right hemispheric activity (Figure 3.9). The subjects had to rotate or process the puzzle pieces in these trials, which require the manipulation of the relevant information. It was shown that working memory tasks that require only maintaining the relevant information in the working memory are less difficult than tasks that require manipulation. Therefore, more difficult tasks (i.e., match and non-match trials) could have led the participants to employ different strategies, which might have induced a significant neuronal activation in the left hemisphere. Post-experiment feedback from the subjects revealed that they had focused on local features (i.e., protrusions) of the pieces and templates as well as using verbalization and/or inner speech. It is known that the left hemisphere is the primary processing region for language [5] and also plays a role in inner speech [6]. It was also shown that inner speech or verbalization is a common strategy employed in mental rotation tasks [152]. Moreover, the left hemisphere was shown to be the dominant hemisphere while processing the local features of complex shapes [165, 166]. Left BA 8, 9, 45, and 46 were among the significantly active regions for match and non-match conditions in the present experiment. These areas are known to be involved in language processing. Thus, bilateral activation found for match and non-match trials was likely to occur as a result of the cognitive strategies used by the participants (Figure 3.9).

The contrast between the conditions revealed significant neuronal activation in the left DLPFC for Match > Perfect Match (Figure 3.10 A). As explained above, subjects have employed other cognitive processes such as verbalization and/or inner speech during match trials, while they did not in perfect match trials. Various studies have shown that linguistic tasks require a left-hemispheric activation [167, 168]. Furthermore, verbalization was shown to be one of the strategies used during mental rotation tasks [152]. Hence, the differential neuronal activity located in the left DLPFC for match trials compared to perfect match trials was likely because of the inner speech or verbalization of the local features in the more complex task (i.e., Match trials). On the other hand, non-match trials created a greater activation than match and perfect match trials in the same region of the right hemisphere (Figure 3.10 B and C). The behavioral findings implied that the match trials should have shown greater neuronal activation than non-match trials. However, the outcome was stronger neuronal activation in the right hemisphere for non-match trials. Furthermore, the non-match trials showed a stronger activation than perfect match trials at the same brain region. Hence, another cognitive mechanism should be responsible for the differential activity caused by non-match trials compared to perfect match and match trials. The difference was that perfect match and match trials were congruent trials requiring approval and 'Yes' response, while non-match trials were incongruent stimuli requiring a rejection and 'No' response. The correct rejection might explain the stronger neuronal activation in the right DLPFC for non-match trials. The right DLPFC was shown to be one of the active brain regions during incongruent trials of the Stroop test [90]. Simmonds et al. (2008) also found an association between the successful inhibition of No-Go trials and the right DLPFC activity [91]. Therefore, neuronal activation of the right DLPFC for the non-match trials compared to perfect match and match trials could be due to the correct rejection.

The mental rotation experiment revealed that the right DLPFC is a core region for performing a visual processing task, as expected. A previous visual processing experiment was carried out with TMT and the findings indicated that the right ear presented greater temperature increase compared to the left ear. Hence, it can be said that these findings are in line with each other, indicating that TMT can reflect the ongoing activity of a hemisphere. Moreover, the present mental rotation experiment showed that the locus and the magnitude of the neural activity was modulated by task difficulty. For future experiments, one should be aware of this drawback. It seems that increased task difficulty forces the brain to employ further cognitive strategies, which can result in bilateral neuronal activity.

3.4.3 Relative Clause Experiment

Background and Introduction.

It was originally thought that language processing occurs only in the left hemisphere. However, further research has shown that the right hemisphere also plays some role in language processing, such as processing prosody [169]. In a review, Mitchell (2005) states that the right hemisphere plays a role in understanding and/or processing metaphors and sarcasm [170]. In another review, Lindell (2006) suggests that the right hemisphere also involves in speech production and visual word recognition [171]. Nevertheless, various studies have shown that the left hemisphere is mainly responsible for syntax processing in different languages [172–175].

Syntax processing has been studied with different paradigms such as garden path sentences [176,177] and center-embedded and right-branching sentences [178,179]. Relative clauses have been widely used in linguistic studies to investigate syntax processing in terms of complexity. Relative clauses can be defined as phrases that add explanatory information to the object or subject of the sentence. Özge et al. (2009) have explained that two suffixes were used to form relative clauses in Turkish [180]. The authors have stated that subject relative clauses (SRCs) are formed with suffix (-(y)AN), while object relative clauses (ORCs) are formed with suffix (-DIK). Below, there are the examples for SRC and ORC containing sentences, respectively:

(1) Hırsızı kovalayan polis nehire atladı.
(The police that chased the burglar jumped into the river.)

(2) Hırsızın kovaladığı polis nehire atladı.
(The police that the burglar chased jumped into the river.)

In the first sentence, the modified noun is the police, and it is the subject of the verb of the embedded clause (i.e., chased the burglar). Therefore, it is defined as subject relative clause. On the other hand, the modified noun (i.e., the police) in the second sentence is the object of the verb (i.e., chase), which makes it object relative clause.

Various studies have compared object relative clauses with subject relative clauses in terms of processing difficulties with different methods such as EEG [181,182], eye tracking [183, 184], and fNIRS [54, 185]. Studies in various languages such as Dutch [186], English [187], and German [188] have shown that processing SRC is easier than processing ORC. Since these languages have different word order (Subject-Verb-Object for English; while Subject-Object-Verb for Dutch and German), it was claimed that easier SRC processing compared to ORC processing is a universal feature for languages. However, studies carried out in Mandarin Chinese produced contradictory results, favoring easier ORC processing compared to SRC [183, 189]. A Basque study also showed that processing ORC is easier than processing SRC [182]. It was claimed that these languages are head-final, thus leading to easier ORC processing. A language can be head-initial or head-final. Head is considered as the determiner element of any phrase. For instance, in a verb phrase (i.e., drink the water), the head is the verb (i.e., drink). English is mainly considered as a head-initial language. It can be seen in the example verb phrase (i.e., drink the water) that the head is before the determiner. It is claimed that Turkish is a head-final language with some flexibility [190]. Thus, ORC processing advantage could be expected in Turkish as well. However, the majority of the studies have found that SRC processing is easier than processing ORC in Turkish [191–195].

The Turkish relative clause studies have employed behavioral metrics such as reading time and eye-tracking. To the best of my knowledge, processing differences between SRC and ORC in Turkish have not yet been investigated with neuroimaging or electrophysiological methods. Neuroimaging studies performed with other languages showed that classical language areas located in the left hemisphere are crucial for processing relative clauses. For example, Caplan et al. (2001) showed that left perisylvian association cortex activity is associated with relative clause processing in a sentence plausibility task. Moreover, they reported that processing object relative clause was more difficult than processing subject relative clause if both clauses have the subject role in the main clause. Kovelman et al. (2008) also demonstrated that monolinguals showed activity in the left inferior frontal cortex (BA 11, 44, 45, and 47) in addition to the right inferior frontal cortex (BA 44 and 45) for processing relative clauses [196]. The neuronal activity in the left BA 44 and 45 (classical language areas including Broca's Area) increased during the task compared to baseline. Furthermore, contrast between ORC and SRC processing revealed that processing ORC is more difficult than processing SRC, causing a greater neuronal activity in the BA 44 and 45 bilaterally, BA 46 and 47 in the right hemisphere. Hassanpour et al. (2015) found that relative clause processing compared to unintelligible speech caused a greater neuronal activity in the left and the right DLPFC [197]. They also found that the left DLPFC shows significantly greater neuronal activity for the ORC>SRC contrast. Lastly, an fNIRS study reported that left DLPFC is one of the active regions for relative clause processing and that a more difficult task caused a greater neuronal activity in both left and right DLPFC [185].

Hypotheses

To sum, there is a robust difference between processing SRC and ORC in terms of cognitive load. Auditory experiments showed that word-level processing caused a greater temperature increase in the left ear, indicating a left-lateralized brain activity. In the present experiment, it was aimed to investigate the hemodynamics of the prefrontal cortex during a sentence level language processing task. The other aim was to investigate the neuronal activity differences between processing SRC and ORC in Turkish in terms of hemodynamic activity strength and location. It was hypothesized that the left hemisphere would be mainly active for both conditions. Moreover, ORC processing was expected to cause greater neuronal activity than SRC processing.

Materials and Method.

In this experiment, subjects were asked to give 'Yes' or 'No' answers to a question about a sentence via keyboard response. The sentences were adapted from Traxler et al. (2002) [184]. All sentences were 10 words long and subjects responded to 24 sentence-question pairs (i.e., trials) in total. Half of the sentences had a subject relative clause (SRC), while the other half had an object relative clause (ORC). The trials were counterbalanced so that 'Yes' answer should be given for half of the questions and 'No' answer should be given for the other half in each condition (i.e., SRC-containing and ORC-containing). Therefore, the subjects responded to six trials for each (condition x answer) structure. In the following sentence-question pair examples, subjects had to say 'Yes' for the first pair and 'No' for the second pair, respectively, via keyboard response. The first sentence-question pair contains a subject relative clause, while the second one object relative clause. The complete stimuli set is provided in Appendix A.3.

(1)
Yaşlı avukatı kızdıran bankacı her cumartesi öğleden sonra tenis oynadı.
(The banker that irritated old lawyer played tennis every Saturday afternoon.)
Bankacı tenis oynadı?
(Did the banker play the tennis?)
(2)
Profesörün eleştrdiği öğrenci dersten sonra kitabın son bölümünü hızlıca okudu.
(The student that the professor criticized read the last chapter of the book quickly after class.)
Profesör son bölümü hızlıca okudu?
(Did the professor read the last chapter quickly?)

The experiment began with a baseline fNIRS recording of 30 seconds, after which the subjects had to press the 'Space' key on the keyboard to start the experiment. A plus sign ('+') was presented for 500 ms before each trial. A randomly chosen sentence was presented on the screen for 4 seconds, immediately followed by the question shown on the screen for 3 seconds, during which the subjects had to give a 'Yes' or 'No' answer by pressing 's' or 'k' on the keyboard, respectively. All sentences and questions were centered on the screen. The total duration of a trial was 7.5 seconds. ISI was set randomly for each trial ranging from 7 to 10 seconds to prevent the subject's anticipatory hemodynamic responses and to match the duration of this experiment with the duration of the mental rotation experiment (Figure 3.11). The experiment was designed with PsychoPy 3.0.6 [142]. PsychoPy was also used to record the reaction times and accuracy rates. fNIRS data were collected continuously during the experiment.

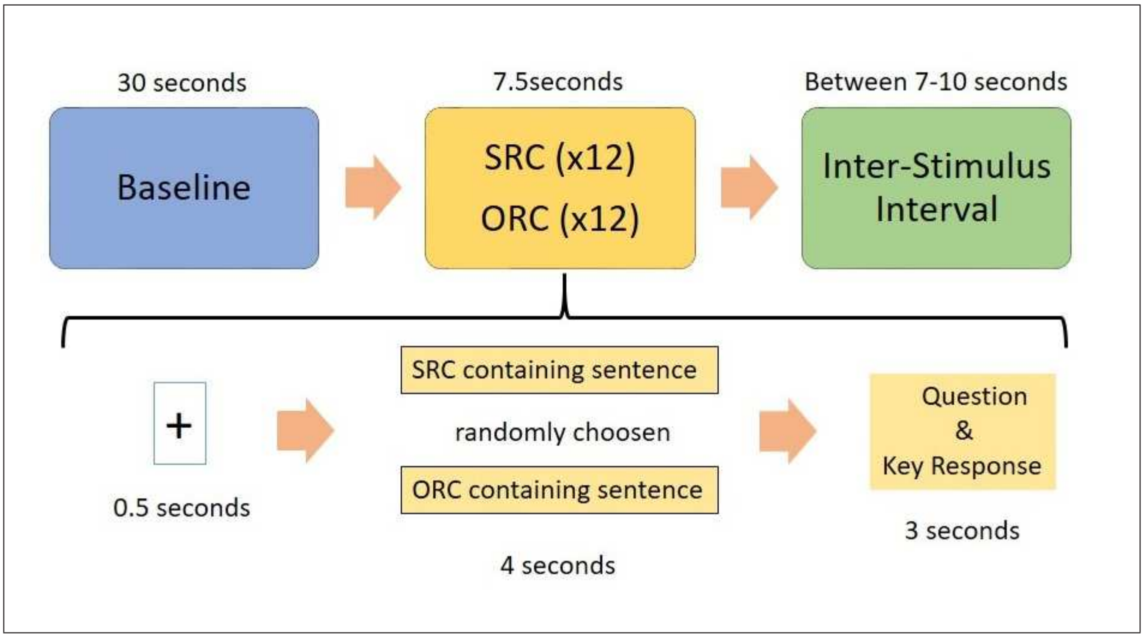

Figure 3.11 Relative Clause Experimental Procedure.

Data Analysis

For each subject, average accuracy and reaction times were calculated for both conditions. Paired sample student t-test was used for analyzing the accuracy and reaction time data sets.

Fourteen second long segments, spanning from 2 s pre-stimulus baseline interval to 12 s long duration after the stimulus, were created for each trial. fNIRS recording system used in this experiment was different than that of used in the word processing experiment. Moreover, these devices have different sampling rates, leading to different post-stimulus activity windows (i.e., 12,5 seconds and 12 seconds). Each segment was detrended and labeled as a subject relative clause (SRC) or object relative clause (ORC) condition trial.

The significantly active brain regions in a subject were localized as follows for both conditions: 1. HAS parameter of each trial (12 for SRC and 12 for ORC) was computed separately for each condition and channel with Eq. 2.5. 2. One sample student t-tests were performed on the HAS values belonging to each condition and channel, separately. 3. Statistically significant channels ($p < 0.05$) were labeled as active channels.

Hemispheric lateralization was calculated with the modified version of Eq. 2.6. The normalization was performed with $N_C = 10$, as there were ten channels in a hemisphere in this probe. Therefore, positive $HL_{sub,con}$ values corresponded to left hemispheric dominance, while the negative values corresponded to the right hemispheric dominance. The hemispheric lateralization vector belonging to each condition was subjected to a one-sample student t-test to assess the hemispheric lateralization. Paired sample student t-test was employed to assess the hemispheric lateralization difference between the conditions.

To localize the significant brain activity at the group level, group-level HAS values were computed as follows: 1. The labeled segments (SRC or ORC) were block averaged to obtain a single 14 seconds long segment for each channel and subject (i.e., there would be two averaged segments, each belonging to one condition, for each channel of a subject). 2. HAS of the block averaged segments was computed for each condition in a subject with Eq. 2.5. 3. 14×2 matrices (subject$\times$condition) were created with the computed HAS values for each channel.

A channel-based one-sample student t-test was performed on group-level HAS matrices to find the significantly active channels in a condition. To investigate the channel-based contrast, paired sample student t-test was employed.

Channels were not included as a main factor in ANOVA analyses, as it was suggested that each fNIRS channel collects signal from different brain region with different optical properties, which can lead a systemic bias in the results [160, 161]. All statistical analyses were conducted with IBM SPSS Statistics 2015 and MATLAB R2017B.

Results.

One subject was excluded from the analysis due to a damaged fNIRS recording file, and three subjects were excluded from the analysis because they failed to answer more than 40% of the trials within the 3 seconds long question-answer interval. The remaining subjects were five females and five males. One subject was left-handed (male), and the mean age was 27.6 ± 3.56.

Accuracy and the reaction time results can be seen in Table 3.4. Even though the subjects had higher accuracy in SRC conditions compared to ORC conditions, the difference was not significant ($t(9)=1.137$, $p=0.285$). ORC containing sentences produced a slightly longer reaction time than SRC containing sentences, yet the difference was not significant ($t(9)=-0.437$, $p=0.672$).

Table 3.4
Behavioral data of Relative Clause experiment.

	Subject Relative Clause	**Object Relative Clause**	**Average**
Accuracy	0.833 ± 0.079	0.775 ± 0.125	0.804 ± 0.106
Reaction time (s)	2.181 ± 0.160	2.206 ± 0.155	2.194 ± 0.154

Hemispheric lateralization of each subject was given in Table 3.5. The excluded subjects (i.e., S1, S2, S6, and S13) were not included in the table. One sample student t-test did not reveal a statistically significant lateralization effect for neither SRC ($t(9)=-0.855$, $p=0.415$) nor ORC ($t(9)=-1.354$, $p=0.209$) conditions. Paired sample student t-test revealed no significant hemispheric lateralization difference between the conditions ($t(9)=0.488$, $p=0.637$).

Table 3.5
Hemispheric lateralization for each condition.

	S3	S4	S5	S7	S8	S9	S10	S11	S12	S14	**mean ± std**
SRC	-0.6	0.5	-0.4	0.1	-0.9	0	0.1	0	0.1	0	-0.11 ± 0.129
ORC	-0.4	0.3	0	-0.2	-0.9	0	0.1	0.2	-0.3	-0.3	-0.15 ± 0.111

Channel-based one sample student t-test analysis revealed a slightly right-lateralized activation for processing SRC condition, while ORC condition generated an activation in a wider frontal area. Figure 3.12 depicts the location of the significantly active channels ($p<0.05$). Channel-based paired sample student t-test did not reveal a statistically significant difference between the conditions for any of the channels ($p>0.05$).

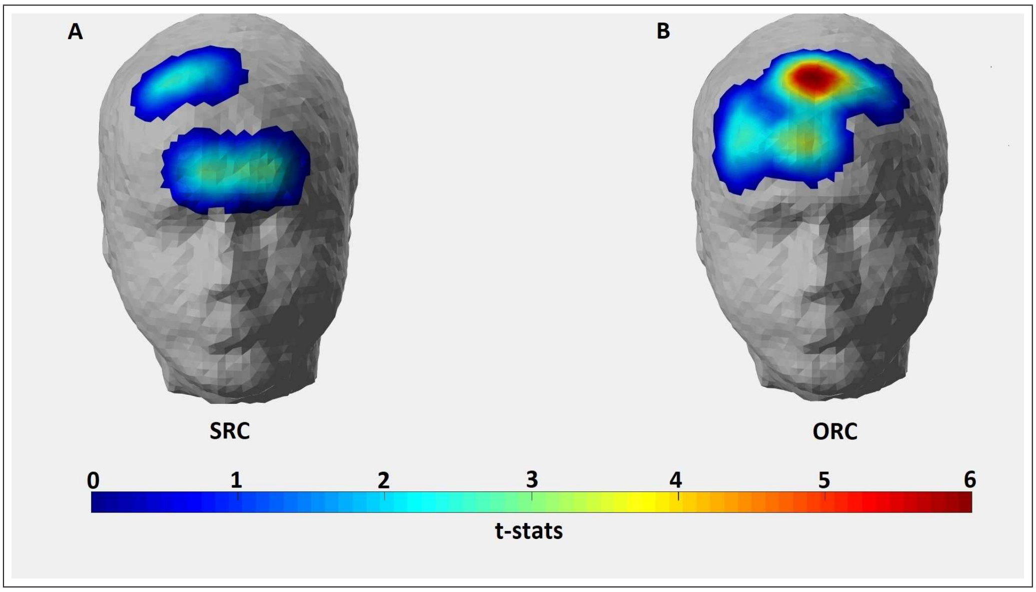

Figure 3.12 Group-level HAS in Relative Clause experiment.

Discussion.

As stated above, the subjects participated in the mental rotation and relative clause experiment in a counterbalanced design. The motivation was to show that visual processing and language processing cause distinct neuronal activity in the brain. The other aim was to provide a neuroimaging basis for future TMT experiments that can be carried out with a novel TMT device developed within the scope of this thesis. It was also aimed to investigate the neuronal activity difference for processing SRC and ORC containing sentences. In summary, results unexpectedly revealed a significant neuronal activation especially in the medial prefrontal cortex (Figure 3.12). On the other hand, the experiment revealed a non-significant tendency for more difficult ORC processing compared to SRC processing in Turkish .

Even though the difference between the conditions failed to reach a statistical significance, accuracy and reaction time results taken together suggested that processing ORC containing sentences seems to be more difficult than processing SRC containing sentences in Turkish. This finding is in line with the previous Turkish relative clause processing studies [191–193].

Hemispheric lateralization results showed that both ORC and SRC conditions caused an unexpected, non-significant slightly right-lateralized activation. Furthermore, group-level HAS analysis revealed that hemodynamic activity was localized in medial regions of the frontal cortex, covering BA 9, 10, and 11 for both processing SRC and ORC. These medial regions are shown to be involved in decision making [198, 199] and several language processing-related mechanisms, including syntax processing [200,201]. Another active region was the right DLPFC, which was also shown to be active during relative clause processing [197]. The subjects made a decision after each sentence in the present experiment. Thus, the elevated hemodynamic activity in these regions could be reflecting the language processing and decision-making-related neuronal activation rather than processing relative clauses. Channel-based contrasts were not statistically significant for HAS parameter. It is possible that there was no difference between processing SRCs and ORCs in terms of hemodynamic activity in Turkish with this experimental design. In an online relative clause comprehension study, Özge et al. divided (object or subject) relative clause containing sentences into five segments and measured the listening time of the subjects [190]. Their results showed that SRCs and ORCs have advantages and disadvantages in different segments of the sentences, yet there was no overall difference between SRC or ORC. Therefore, it could be said that processing SRC and ORC is at the same difficulty level in terms of hemodynamic activity. On the other hand, further analysis showed that hemodynamic activity strength (HAS) values of ORC conditions were non-significantly greater than that of SRC conditions especially in Broca's area (left BA 44 and 45) and left DLPFC (BA 46) in the present experiment. Numerous studies have also found that the neuronal activity of the left DLPFC increases with task difficulty in relative clause processing [196,197]. Kovelman et al. (2008) have also specifically mentioned the increased neuronal activity in the left BA 44 and 45 for more difficult relative clause tasks. Furthermore, Figure 3.12 shows that eight channels presented a significant activity in the ORC condition, while there were only five active channels in SRC conditions, implying a more widespread neuronal activity in the prefrontal cortex for ORC conditions. A further investigation revealed that ORC conditions produced greater neuronal activity measured by HAS in four out of five channels covering the brain regions known for language processing. Based on these it can be said that processing ORC is more difficult than processing SRC in Turkish.

To conclude, behavioral parameters (i.e., accuracy and reaction time) and HAS findings -more widespread activity in prefrontal regions and non-significant greater hemodynamic activity in left BA 45, 46- implies that processing ORC was cognitively more demanding and more difficult than processing SRC in Turkish. However, contrary to initial expectations it was found that the right hemisphere is also involved in syntax processing in Turkish. There could be several factors that prevented significant difference between SRC and ORC conditions. First, the analyses were performed with ten subjects because of excluding four subjects due to low accuracy levels or damaged files. Secondly, relative clauses used in the experiment might not have been sufficiently difficult for the subjects. Each sentence had a pair of actors in the present experiment, while it is possible to use three or more actors in the main clause or relative clause to increase the complexity and difficulty. Lastly, subjects were exposed to twelve sentence-question pairs in each condition in a mixed design, and the limited number of stimuli could be another reason.

This experiment was carried out to reveal the neural hemodynamics of the prefrontal regions during syntax processing. The initial hypothesis was to find a significant activity in the left hemisphere, contrary to the mental rotation task that was expected to induce right hemispheric activity in general. However, findings revealed that the medial and right prefrontal cortex are also involved in relative clause processing in Turkish. Albeit non-significant, ORC containing sentences caused a greater hemodynamic activity than SRC containing sentences especially in the most lateral regions of the left hemisphere, indicating ORC>SRC in terms of processing difficulty. Future experiments should be conducted with increased number of subjects as well as larger number of more complex stimuli set.

4. GENERAL CONCLUSION

In the present dissertation, the main aim was to investigate and compare the cognitive costs of processing words from Turkish and English languages. To that end, ear temperature and the hemodynamic activity of the brain were measured in three word processing experiments. There were also some secondary aims of the present dissertation. One was to show that simple, non-invasive TMT measurement can reliably dissociate the lateralized brain activity induced by different cognitive tasks, namely language processing and visuospatial processing. Moreover, it was also aimed to demonstrate that TMT can reflect the task difficulty of various cognitive tasks. For that aim, a visual processing experiment was carried out during which the subjects' ear temperatures were recorded with TMT. An additional goal was to develop novel experiments (i.e., visual and language processing) to be used in future TMT studies. Sentence processing and visual processing experiments were developed and the brain dynamics were investigated with fNIRS also to show that language processing and visual processing induce neuronal activation in distinct brain regions. Lastly, it was aimed to develop a novel tympanic membrane thermometer that has superior technical capabilities to the commercially available ones.

Language is a crucial cognitive skill for human beings. As stated earlier, languages differ from each other in terms of linguistic features such as syntax, lexicon, grammar, etc. On the other hand, native speakers of different languages seem to have equal or similar competence in linguistic performance. This fact suggests that the brains of different language speakers can show the same performance despite using different languages. Nevertheless, it can be said that distinct linguistic features of languages would cause distinct neuronal processing in the brain. Different languages have been investigated and compared in a variety of experimental designs for different linguistic features [25, 76, 98, 101, 102, 178, 186, 191]. Language processing has also been investigated in terms of cognitive load [202–204]. However, to the best of my knowledge, none of the previous studies attempted to quantify the cognitive load of processing different languages. Furthermore, ear temperature measurement has also been used to investigate the cognitive load of various cognitive skills such as language [25, 35], visual processing [25, 35], emotion processing [24, 27], impulsivity [41]. These studies attempted either dissociating the left vs. right hemispheric activity with ear temperature measurement or directly capturing a lateralized brain function. On the other hand, the present dissertation aimed to investigate and quantify the cognitive load and energy consumption of processing words from native and non-native languages. Auditory experiments were designed and carried out to achieve this goal. In auditory experiments, subjects were divided into three experimental groups (passive listening; word memorizing; word counting) and listened to a word list consisting of Turkish and English words. The temperature findings of auditory experiments showed that word processing caused a greater temperature increase in the left ear temperature in general, reflecting left-lateralized language processing. The experiments also revealed that processing words from non-native language was more difficult than processing words from native language, and that task difficulty was reflected in the ipsilateral ear temperature increase, as shown by the greatest temperature increase in the left ear of the word group (i.e., the group who had the most difficult task). These experiments demonstrated that the cognitive cost of processing linguistic material can be quantified via ear temperature measurement.

In the last auditory experiment, simultaneous TMT and fNIRS recordings have been performed for the first time in the literature. As explained above, fNIRS measures neuronal activity based on the changes in the blood oxyhemoglobin and deoxyhemoglobin levels. TMT is also known to be affected mainly by the blood flow [37, 43]. In other words, since TMT and fNIRS techniques are based on a common underlying phenomenon, it was expected to find similar or parallel results. Indeed, findings of the last auditory experiment showed that words from non-native language caused greater temperature increase in the left ear as well as greater neuronal activity in the left hemisphere. Furthermore, the greater temperature and/or hemodynamic activity changes were present in TMT and fNIRS findings of the word group. This experiment also showed that activity in the right DLPFC could be crucial for ambiguity resolution while processing interlingual words. To sum, fNIRS findings also supported the view that processing words from a non-native language is cognitively more demanding than processing words from a native language, causing greater hemodynamic response especially in the left DLPFC.

Even though the relationship between fNIRS and TMT was shown in the last auditory experiment, it was decided to perform another experiment that included a cognitive task known to induce right-lateralized brain activity (i.e., visuospatial processing). In the first visual processing experiment, subjects visually discriminated target objects from non-target objects, resulting in a greater temperature increase in the right ear. It is suggested that the right hemisphere is the main source of neuronal activation for visuospatial processing [25, 129, 130]. Taken together with the auditory word processing experiments, it can be claimed that the simple, non-invasive TMT method can be used in cognitive paradigms to dissociate the left vs. right hemispheric activity.

Despite not being the main focus of the present dissertation, findings of the TMT experiments have an implication for theories regarding the TMT-brain activity relationship. As stated above, two theories were suggested to explain the relationship between neuronal activity and the ear temperature changes in the ipsilateral ear: increased neuronal activity-decreased ear temperature [25, 33, 37] and increased neuronal activity-increased temperature [24, 35]. In all TMT experiments (i.e., three auditory and one visual experiments), ear temperatures were found to be increased in the present dissertation. Therefore, it can be claimed that one should expect to find an increase in the ipsilateral ear temperature for increased neuronal activity in a hemisphere or increased task difficulty.

Two novel experiments were developed within the scope of the present thesis: mental rotation and relative clause processing. These experiments were carried out to show that visual processing and language processing cause neuronal activation in different brain regions. In the mental rotation experiment, the task consisted of three difficulty levels. As expected, the right hemisphere showed significant activity in all difficulty levels. The right-hemispheric superiority has been suggested for visual processing tasks in general [25, 122–126, 133]. Consistent right DLPFC activation across difficulty levels in the present dissertation also suggests the significant role of the right hemisphere in visual processing. Furthermore, it was found that relatively more difficult tasks (i.e., match and non-match conditions) caused bilateral activations and the most difficult task (i.e., match condition) caused the strongest activity in the prefrontal cortex. Some mental rotation studies have claimed that the right hemisphere is responsible for performing mental rotation [127–129]. However, it was also suggested that task difficulty can cause a bilateral [149, 156] or even left-hemispheric activity [154]. Left hemispheric dominance reported by Mehta and Newcombie (1991) was claimed to be caused by the three-dimensional objects used in the experiment [159]. However, the mental rotation experiment of the present dissertation showed that even two-dimensional mental rotation tasks can induce a left hemispheric neuronal activity if the task requires further cognitive strategies.

In the relative clause experiment, subject vs. object relative clause processing task was used, as it was shown that syntax processing mainly activates the left hemisphere [172–174]. Unexpectedly, the relative clause experiment did induce significant neuronal activity mainly in the medial prefrontal cortex regions, rather than in the left hemisphere. However, accuracy, reaction time and hemodynamic activity especially in the left Broca's Area revealed a non-significant ORC>SRC contrast. These findings imply that processing ORC in Turkish can be cognitively more demanding than processing SRC. It should also be noted that this experiment was the first Turkish relative clause study carried out with a neuroimaging method since the previous studies used behavioral metrics [191–195]. Even though the experiment suggested ORC>SRC in terms of cognitive cost, the findings were not conclusive. Hence, further relative clause experiments in Turkish should be carried out with brain imaging techniques.

The Hemodynamic Activity Strength (HAS) parameter was first introduced in a paper [130] published within the scope of the present dissertation. Even though the practices are similar to some extent, there is still no consensus on how to preprocess and analyze the fNIRS data in the literature [106, 205, 206]. Therefore, developing HAS can be considered as a contribution to the fNIRS field in general.

Lastly, a new infrared thermometer was developed with a 100 Hz sampling rate and 0.01 °C resolution, outperforming the commercially available thermometers. TMT studies have been carried out with commercial ear thermometers [17, 22, 24, 27], except two studies [25, 43]. The performance of the commercial thermometers could be limiting since they cannot measure ear temperature continuously and have a low resolution (0.1 °C in general). Thus, a tympanic membrane thermometer with superior technical ability would allow investigating the brain energy dynamics with higher temporal resolution.

4.1 Future Directions

Verbal auditory experiments revealed a significant temperature difference between groups, reflecting the processing difficulty differences of words from the native and non-native languages. However, TMT experiments (both auditory and visual) failed to find a significant difference between Turkish and English words (or target and non-target puzzle pieces in a visual experiment) in direct comparison. To recap, subjects were listening to English and Turkish words (seeing the target and non-target puzzle pieces) in a mixed order. The event-related design of these experiments might have led to a cumulative effect, thus preventing an item based difference. Therefore, performing the same or similar experiment with a block design would be more informative.

Another insightful study can be to investigate how the number of target (or non-target) items affects the ear temperature dynamics. As demonstrated by auditory experiments, task difficulty affects the amount of temperature increase. An experiment with an increased (or decreased) number of target items (i.e., words or shapes) in conditions may allow direct quantification of how does brain energy consumption is affected by the cognitive load, induced by a different number of stimuli. It was also found in TMT experiments that the increased neuronal activity cause increased temperature in the ipsilateral ear. It can be safely assumed that the temperature increase would stop at some point to prevent damage to the brain. Therefore, investigating the relationship between ear temperature increase and the brain's information processing capacity, by increasing the cognitive or processing load, would shed light on the physiological limits and capabilities of the brain.

The scope of the present dissertation was mainly focused on comparing native and non-native languages at the word processing level. However, we take advantage of and use phonetics, grammar, orthography and so on to successfully communicate with our peers. It can be expected that energy requirements and dynamics of the brain would be different at sentence or discourse level processing. Therefore, investigating sentence-level and/or discourse level language processing can be valuable, since it may allow measuring and quantifying the cognitive cost of language in a more naturalistic scenario.

APPENDIX A. FULL STIMULI LIST

A.1 Word Level Auditory Experiment 1

Table A.1
Full word list ordered according to their presentation order.

Order	Word	Translation	Order	Word	Translation
1	Göz	Eye	**16**	Shark	-
2	Çöl	Desert	**17**	Kalp	Heart
3	Gene	-	**18**	Tuz	Salt
4	Bal	Honey	**19**	Tül	Tulle
5	Muz	Banana	**20**	Süt	Milk
6	Kuş	Bird	**21**	Pie	-
7	Short	-	**22**	Fish	-
8	Cell	-	**23**	Naz	Coyness
9	Taş	Stone	**24**	Sis	Mist
10	Çöp	Garbage	**25**	Car	-
11	Saz	Reed	**26**	Yurt	Homeland
12	Ders	Lesson	**27**	Boy	-
13	Leaf	-	**28**	Kış	Winter
14	Zar	Dice	**29**	Shop	-
15	Genç	Young	-	-	-

A.2 Word Level Auditory Experiment 2

Table A.2
Full word list ordered according to their presentation order.

Order	Word	Tur. Freq.	Eng. Freq.	Translation
1	Kıl	45	-	Bristle
2	Suç	221	-	Crime
3	Boy	130	221	Height
4	Sır	131	-	Secret
5	Çöp	126	-	Trash
6	Tüy	78	-	Feather
7	Bye	2	82	Mister
8	Dev	114	-	Giant
9	Ten	155	81	Skin
10	Boş	238	-	Empty
11	Tıp	55	-	Medicine
12	Ses	1	-	Sound
13	Dish	16	151	Tooth
14	Bell	18	77	Waist
15	Kuş	129	-	Bird
16	Gül	116	-	Rose
17	Phone	10	139	Fund
18	Yaz	191	-	Summer
19	Dün	180	-	Yesterday
20	Pie	72	152	Share
21	Süt	200	-	Milk
22	Ball	10	131	Ample
23	Çay	175	-	Tea
24	Cep	144	-	Pocket
25	Car	267	79	Snow
26	Tuz	189	-	Salt
27	Kaş	58	-	Eyebrow
28	Zar	46	-	Dice
29	Tell	265	77	Wire
30	Kök	85	-	Root

A.3 Visual fNIRS Experiment

1. **Bebek bakıcısını kovalayan sarı saçlı çocuk oyun oynarken çığlık attı.**

   The yellow-haired child that chased the babysitter squealed while playing.

   Bebek bakıcısı çığlık attı?

   The babysitter squealed?

2. **Oyun kurucudan nefret eden defans oyuncusu kötü bir espri yaptı.**

   The linebacker that hated the quarterback made a bad joke.

   Defans oyuncusu oyun kurucudan nefret ediyordu?

   The linebacker hated the quarterback?

3. **Hemşireyi görmezden gelen doktor üstü açılabilen kırmızı bir araba kullandı.**

   The doctor that ignored the nurse drove a red convertible.

   Hemşire doktoru görmezden geldi?

   The nurse ignored the doctor?

4. **Yaşlı yazarı öven genç fotoğrafçı ulusal bir dergide çalışmak istemiyordu.**

   The young photographer that complimented the old writer did not want to work for a national magazine.

   Fotoğrafçı dergide çalışmak istemiyordu?

   The photographer did not want to work for a magazine?

5. **Yaşlı avukatın kızdırdığı bankacı her cumartesi öğleden sonra tenis oynadı.**

   The banker that the old lawyer irritated played tennis on Saturday afternoons.

   Yaşlı avukat tenis oynadı?

   The old lawyer played tennis?

6. **Kabin memurunun iltifat ettiği pilot işten sonra yemek teklifinde bulundu.**

   The pilot that the flight attendant complimented asked for a dinner after work.

Kabin memuru pilota iltifat etti?

The flight attendant complimented the pilot?

7. **Postacının telefonla aradığı sekreter üç gün önce yeniden hastaneye yattı.**

   The secretary that the postmen called went into hospital again three days ago.

   Sekreter postacıyı aradı?

   The secretary called the postmen?

8. **Garsonun boşadığı tamirci çoğunlukla eve geç saatlerde dönmek zorunda kalıyordu.**

   The mechanic that the waitress divorced often had to get home late.

   Tamirci eve geç dönüyordu?

   The mechanics got home late?

9. **Editörü kızdıran yazar kararı protesto etmek için bir makale yazdı.**

   The writer that angered the editor wrote an article to protest the decision.

   Editör makale yazdı?

   Editor wrote an article?

10. **Yönetmeni beğenen dansçı şehir dışındaki bir okulda özel ders veriyordu.**

    The dancer that admired the director was teaching at a school outside the city.

    Dansçı yönetmeni beğendi?

    The dancer admired the director?

11. **Ev sahibine hakaret eden kiracı sonunda gazeteye şikayet telefonu açtı.**

    The tenant that insulted the landlord finally phoned the newspaper to complain.

    Ev sahibi kiraciya hakaret etti?

    The landlord insulted the tenant?

12. **Sarışın kovboyu öldüren şerif eski bir viski şişesi gibi kokuyordu.**

    The sheriff that killed the blonde cowboy smelled like an old whiskey bottle.

    Şerif viski şişesi gibi kokuyordu?

    The sheriff smelled like a whiskey bottle?

13. **Maharetli hırsızın korkuttuğu yeni polis belinde bir tabanca daha taşıyordu.**
    The new policeman that skilful thief scared was carrying another gun in his waistband.
    Hırsız bir tabanca daha taşıyordu?
    The thief was carrying another gun?

14. **Tecrübeli gardiyanın saldırdığı mahkum fırsatını bulup ceza evinde isyan başlattı.**
    The prisoner that the experienced guard attacked found a way to provoke a riot in the prison.
    Gardiyan mahkuma saldırdı?
    The guard attacked the prisoner?

15. **Kampçının yürüyerek yanından geçtiği şanslı balıkçı sırtında olta takımı taşıyordu.**
    The lucky fisherman that the camper walked past was carrying fishing gear on his back.
    Balıkçı kampçının yürüyerek yanından geçti?
    The fisherman walked past the camper?

16. **Çocuğun yardım ettiği asker savaştan sonra ordudan bir madalya aldı.**
    The soldier that the child assisted received a medal from the army after the war.
    Asker madalya aldı?
    The soldier received a medal?

17. **Elektrikçiye yardım eden muslukçu yirmi yıl çalıştıktan sonra emekli oldu.**
    The plumber that helped the electrician retired after twenty years on the job.
    Elektrikçi emekli oldu?
    The electrician retired?

18. **Yardımcıdan hoşlanan golfçü profesyonel turnuvada son turu epey zorlanarak geçti.**

The golfer that liked the caddy passed the last round in the professional tournement with great difficulty.

Golfçü yardımcısından hoşlandı?

Golfer liked the caddy?

19. **Yeni öğrenciyi eleştiren tarihçi olaydan sonra kendini gerçekten kötü hissetti.**

    The historian that criticized the new student felt really bad after the incident.

    Öğrenci tarihçiyi eleştirdi?

    The student criticized the historian?

20. **Kurda yaklaşan geyik çiçeklerle kaplı çayırı boydan boya koşarak geçti.**

    The deer that approached the wolf sprinted away accross the meadow full of flowers.

    Geyik boydan boya koşarak geçxti?

    The deer sprinted across?

21. **Profesörün eleştirdiği öğrenci dersten sonra kitabın son bölümünü hızlıca okudu.**

    The student that the professor criticized read the last chapter of the book quickly after the class.

    Profesör son bölümü hızlıca okudu?

    The professor read the last chapter quickly?

22. **Psikoloğun ulaşamadığı yeşil gözlü danışman o gece sinemaya gitmekten vazgeçti.**

    The green eyed client that the psychologists could not reach decided not to go to cinema that night.

    Psikolog danışmana ulaşamadı?

    The psycholog could not reach to client?

23. **Acemi avcının gördüğü kamuflajlı bekçi havaya doğru uyarı ateşi açtı.**

    The camouflaged game warden that the novice hunter saw fired a warning shot into the air.

Bekçi acemi avcıyı gördü?

The game warden saw the novice hunter?

24. **Yönetmenin ziyaret ettiği aktör yeni filmde yan rollerden birini kaptı.**

    The actor that the director visited got one of the side roles in the new movie.

    Aktör yan rolü kaptı?

    The actor got the side role?

APPENDIX B. TMT DEVICE DESIGN

B.1 Introduction

It was mentioned in the previous sections that the ear temperature measurements are sensitive to various factors and can be affected easily. Moreover, technical specifications of the commercial ear thermometers are not sufficient to monitor tympanic temperature changes precisely. Therefore, one of the aims of the present thesis was to develop a novel tympanic thermometer with superior technical specifications such as accuracy, resolution, continuous recording mode.

B.1.1 Temperature Measurement Technology

Human body temperature has been measured by employing various techniques such as traditional mercury thermometers, digital contact temperature sensors, and non-contact temperature sensors. Each technique takes advantage of a different physical phenomenon. The traditional thermometers are based on the expansion of liquid mercury with heat. On the other hand, digital contact and non-contact thermometers require further hardware and different types of transducers.

Thermistors are special resistors whose resistance values change with temperature [207]. Thermistors are classified as having either a positive temperature coefficient (PTC) or negative temperature coefficient (NTC) [208]. The resistance of PTC thermistors increases with temperature, while that of NTC thermistors decreases with increased temperature. Furthermore, the relationship between the temperature and the resistance is non-linear. Another component used for temperature measurements is called resistance temperature detector (RTD). The working principle of RTD is fundamentally the same as PTC thermistors; i.e., resistance increase with temperature increase. Mostly a pure material (e.g., platinum) is used in RTD sensors. Unlike thermistors, the relationship between the temperature and resistance in RTD sensors is nearly linear over a relatively large range. On the other hand, thermistors outperform RTDs in terms of resolution because the same amount of temperature changes cause greater resistance changes in thermistors compared to RTDs. Thermocouples are other components used for measuring temperature. A thermocouple consists of two dissimilar metals joined together on one end, while the other hands are left open [207]. The temperature difference between the common end (i.e., joint end) and the open end induces voltage due to the thermoelectric effect [209]. And, the generated voltage is proportional to the temperature difference of the common and open ends. Each method has advantages and disadvantages in terms of specifications such as response time, sensitivity, measurement range, accuracy, stability, etc. However, they can measure the temperature of either their local surroundings or the temperature of the materials, with which they have physical contact.

In the present thesis, the purpose of developing a new thermometer was to measure the tympanic membrane temperature. This aim could not be achieved by utilizing the above mentioned methods, as it involves great risks to get in contact with the tympanum. Therefore, a non-contact or infrared temperature measurement method is required for TMT measurement. Non-contact or radiation thermometry measures the temperature of an object based on the black body thermal radiation. Any object with a temperature higher than absolute zero emits infrared radiation thanks to the movement of the molecules [207]. Infrared non-contact sensors are equipped with a thermopile (i.e., multiple thermocouples connected in series) to convert the thermal radiation into an electronic signal. However, a major drawback of infrared thermometry is that the generated signal is relatively weak and requires amplification and processing.

As a result, use infrared sensors were decided to be used in developing a tympanic membrane thermometer. In the following sections, the sensor selection, system design, system layers and calibration procedures were explained.

B.2 Sensor Selection

Infrared sensors produced by different companies such as Dexter Research Center (Michigan, USA), Exergen Corporation (Massachusetts, USA), Melexis Inc. (Belgium) have been compared in terms of various parameters such as accuracy, resolution, sampling rate, the field of view, and dimension. An infrared thermopile from Dexter Research Center, ST60 with Micro-To packaging, was selected (Figure B.1). The diameter of the sensors was 4.2 mm diameter, the resolution was 0.01 °C, and the field of view was 75°. It was shown that the temperature radiation of the human body peaks around 10 - 14 micrometers [210]. These sensors were equipped with long-wave pass silicon filters with a bandpass of 6.5 - 20 micrometers, which makes them suitable for measuring the thermal radiation of the tympanum. These parameters made this sensor the most suitable option for the purpose.

Figure B.1 Dexter ST60 Micro-To packaging infrared sensor.

B.3 System Overview and Design

In general, infrared sensors produce a voltage based on the temperature difference between the target object (or surface) and the ambient temperature. The temperature of the sensor itself is assumed to be the same as the ambient temperature. Thus, infrared sensors are equipped with two components to perform two measurements: the temperature of the sensor itself (i.e., ambient temperature) and the voltage output produced by the temperature difference between the sensor and the target surface.

Infrared sensors are generally equipped with a thermistor to measure the ambient temperature (i.e., the sensor itself). The resistance changes of the thermistor should be captured to measure the temperature of the sensor itself. Resistance can be measured by injecting a current into the resistor and measuring the voltage simultaneously. A stable and robust current source is required for precise thermistor measurements. Thermistor measurements rarely require amplification as the output signal (i.e., voltage) level can be adjusted via the amplitude of the injected. However, the analog signal should be converted into a digital signal before sending it to the microprocessor and/or computer to be used in target temperature calculations.

Unlike thermistors, the output of a thermocouple is a very weak voltage signal that needs to be amplified. Subsequently, the amplified signal should be converted into a digital signal via an analog-to-digital converter (ADC) before sending to the microprocessor and then to a computer.

In general, the temperature measurement system consists of four stages: sensors, amplification, analog-to-digital conversion, and the microprocessor (Figure B.2). The microprocessor sends the data to a computer via Bluetooth.

Figure B.2 Overall Design of the TMT Measurement System.

B.3.1 System Stages

As the sensor selection and parameters have been provided above, this section includes amplification and filtering, analog-to-digital conversion, and microprocessor stages.

Amplification.

The Dexter Research Center offers a general-purpose miniature amplifier circuit for a variety of infrared sensors. This circuit amplifies the thermopile output signal 1000 times, while the thermistor output is not processed. I have increased the amplification factor to 1333 to increase the signal resolution. The schematic of the amplification stage can be seen in Figure B.3. 1.25 V voltage regulator was included in the original circuit design to guarantee zero thermopile output when the temperature of the target (i.e., ear membrane) is equal to the temperature of the sensor (i.e., ear canal). In total, the system had two amplifying circuits, each process the thermistor and thermopile signals of one sensor independently.

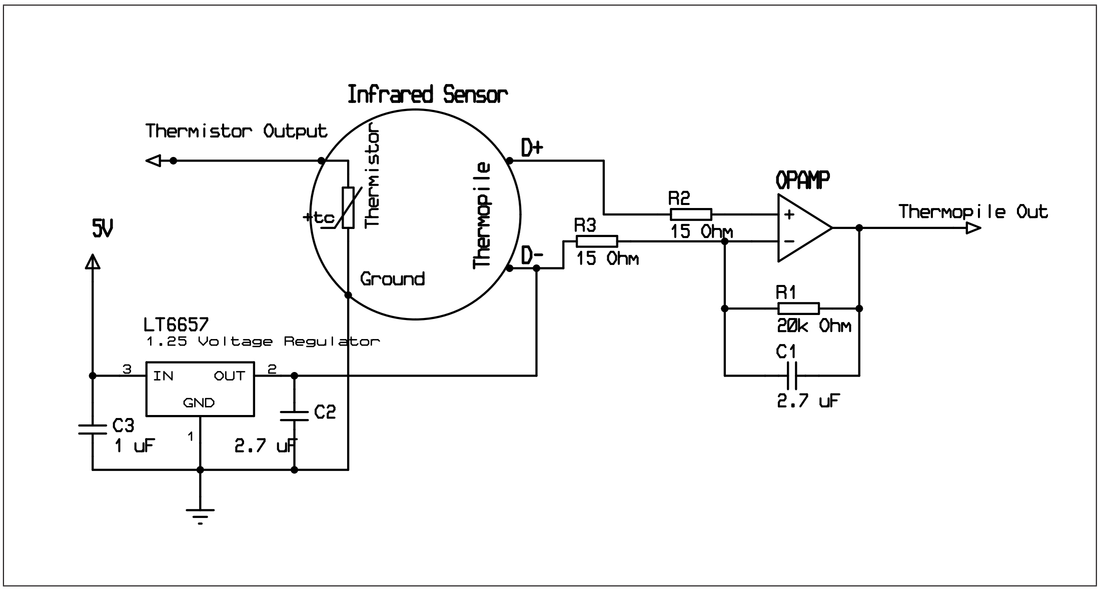

Figure B.3 Circuit schematic of amplifying layer.

The following parts were used in each amplification circuit:

- Analog Devices - AD8628 - Operational Amplifier
- Analog Devices - LT6657 - 1.25 Volt Precision Voltage Reference
- Yageo - 15 Ohm Resistor (2 pieces)
- Yageo - 20 kOhm Resistor

- Kemet - 2.7 μF Capacitor
- Kemet - 1 μF Capacitor
- Panasonic - 2.7 μF Capacitor

Analog-to-Digital Conversion.

LMP90100 (24-bit ADC) from Texas Instruments was selected as an analog-to-digital converter for various reasons. The developed thermometer system requires four independent measurements simultaneously: two for thermopiles and two for thermistors. The first advantage of LMP90100 was that it allows performing four simultaneous measurements. As stated above, thermopile sensors were equipped with a thermistor to measure the ambient (i.e., sensor) temperature, which requires a current source. The other advantage of LMP90100 was that it has two independent current sources. Thus, each current source can be used to measure the temperature of one sensor. The last advantage of LMP90100 for the present system design was that it is possible to increase the sampling rate of each measurement. The sampling rate of the system was increased by adding a 6.7458 MHz crystal. As a result, each of four channels (two thermopiles and two thermistors) was sampled at approximately 101 Hz. The schematic of the LMP90100's connection can be seen in Figure B.4.

The blue box shows the voltage supply connection, while the yellow box shows the current source outputs used to inject current into the thermistor of each sensor. The red box shows the four differential inputs coming from two thermistors and two thermopiles. The orange box depicts the connection between the LMP90100 and the microprocessor (Texas Instruments MSP430F5529), and the green box shows the crystal connection.

The following parts were used in the LMP90100 circuit:

- Texas Instruments - LMP90100 - 24-Bit Low-Power Sigma-Delta ADC
- Abracon - 6.7458 MHz crystal
- Kemet - 18 pF Capacitor (2 pieces)
- Kemet - 1 uF Capacitor (2 pieces)
- Murata - 0.1 uF Capacitor (2 pieces)
- Tajyo Yuden - 100 uH Inductor (2 pieces)

The quality and the consistency of the analog to digital conversion can be affected by various factors. The stability of the reference voltage provided to the chip could be the most important factor. Since the conversion of analog signal to digital signal occurs based on the voltage reference provided to the ADC chip, fluctuations or instability in the voltage reference can cause the output signals to differ greatly from the actual value. Therefore, an ultra-low-noise voltage regulator was added to the system to provide a stable voltage reference for ADC. The schematic of the linear regulator can be seen in Figure B.5. LT3042 (Analog Devices) was used as the output can be adjusted via a single resistor. In addition, it had a superior noise performance. The chip was supplied with 5 volts via a battery (see section Microprocessor and Battery) and provided a clean, low-noise 3.3-volt output. The output of this circuit was used as an analog voltage supply for LMP90100.

The following parts were used in the voltage regulator circuit:

- Analog Devices - LT3042 - Ultralow Noise Linear Regulator
- Yageo - 453 kOhm Resistor
- Yageo - 200 kOhm Resistor

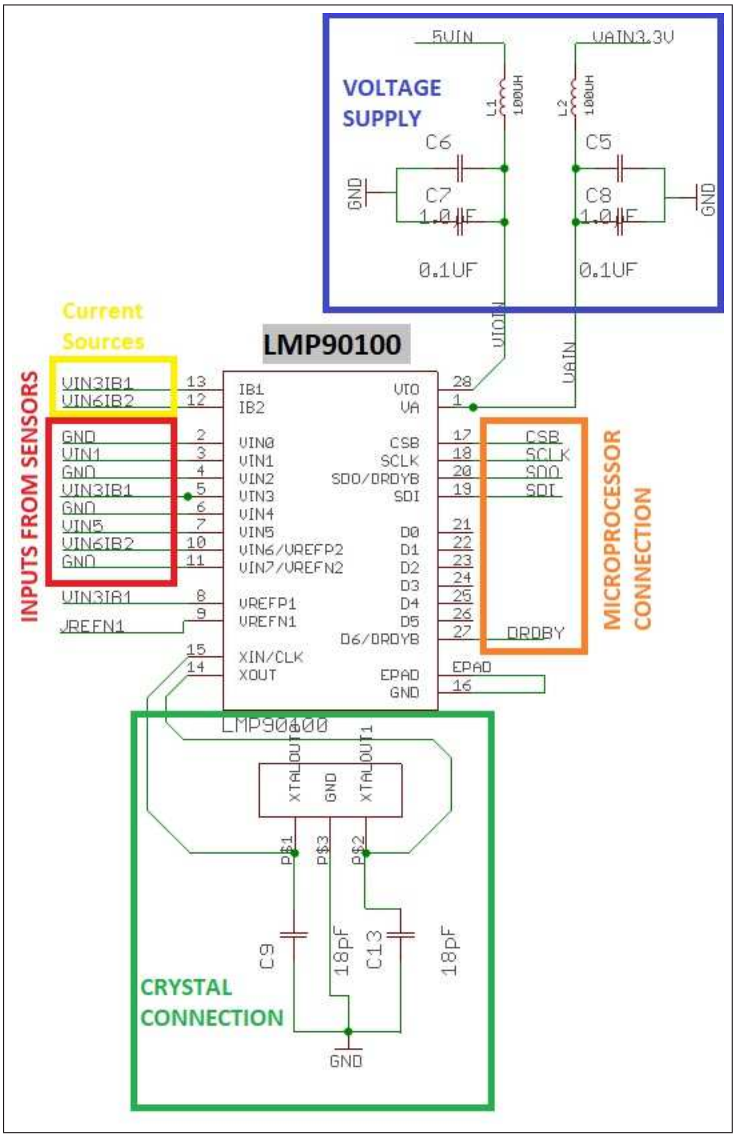

Figure B.4 Circuit schematic of LMP90100.

- Yageo - 49.9 kOhm Resistor
- Yageo - 33.2 kOhm Resistor
- Yageo - 499 Ohm Resistor
- Kemet - 4.7 μF Capacitor (3 pieces)
- Murata - 1 μF Capacitor

Figure B.6 shows the amplification and ADC stages of the developed circuit on a single board. The board was placed within a metal box to minimize the ambient

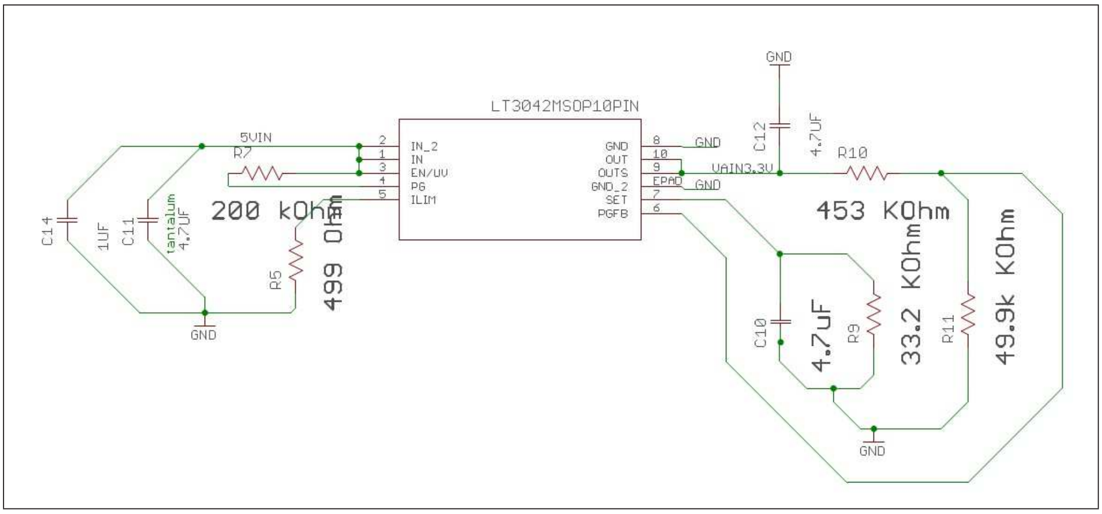

Figure B.5 Circuit schematic of the voltage regulator.

interference on signals.

Microprocessor and Battery.

The digitized data is sent to a microcontroller, which in turn transmits the digitized data to a computer. MSP430F5529 (Texas Instruments) microcontroller was selected as it has a very low power consumption. Moreover, Texas Instruments have an established code and application library for using MSP430F5529 and LMP90100 together in a temperature measurement setup. MSP430F5529 microprocessor can be seen in Figure B.7. The Orange box shows the pins used for communicating with LMP90100, while the black box on the left shows the pins used for connecting the Bluetooth module.

The microcontroller receives four independent data streams (thermistor and thermopile for each sensor), then sends them to a computer via Bluetooth continuously. HC 06 Bluetooth module was used to establish the communication between the microcontroller and the computer (Figure B.8).

The system was powered up by a battery to avoid line interference. BOOSTXL-BATPAKMKII, a battery module from Texas Instruments, was used. This piece of

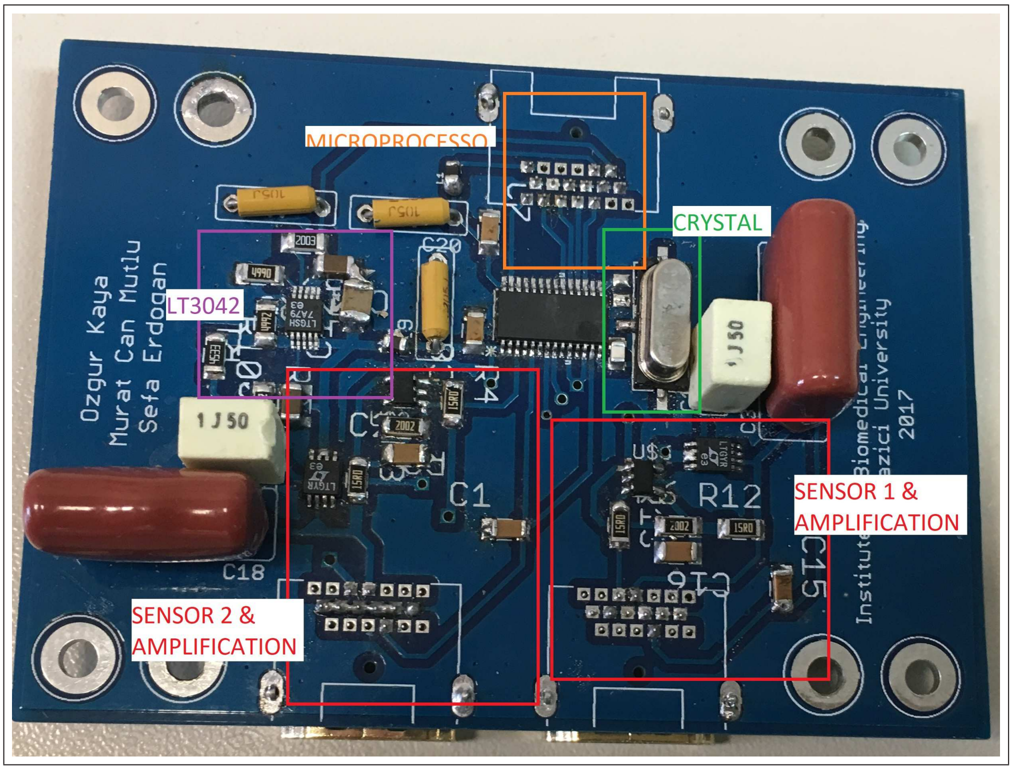

Figure B.6 Amplification and ADC circuit.

equipment has a rechargeable 3.7 Volt lithium battery which can be charged easily via a micro USB connection thanks to the charger unit implemented on the battery module. Moreover, the module has a switch so that the systems powered by BOOSTXL-BATPAKMKII can be turned on or off (Figure B.9). The battery module can be stacked on microcontroller MSP430F5529, which also provides an advantage in terms of the system compactness. The connected microcontroller, Bluetooth module, and battery module can be seen in Figure B.10. A custom-made connector circuit for the HDMI cable was used to connect the microcontroller and ADC circuit.

The Integrated System.

The integrated system can be seen in Figure B.11. The system was developed to measure the tympanic membrane temperature, which requires the sensors to be placed within the ear canal as further as possible. Placing sensors directly within the ear canal can be harmful to both participants' health and sensors. Therefore, I have made

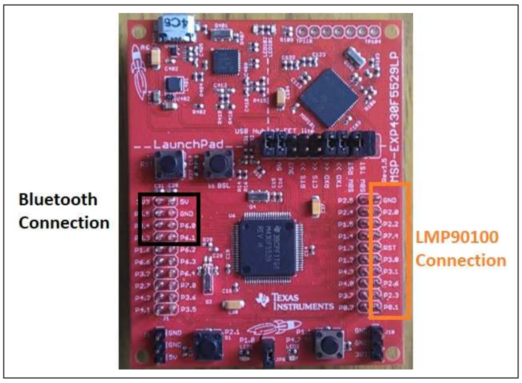

Figure B.7 Texas Instruments MSP430F5529 microcontroller.

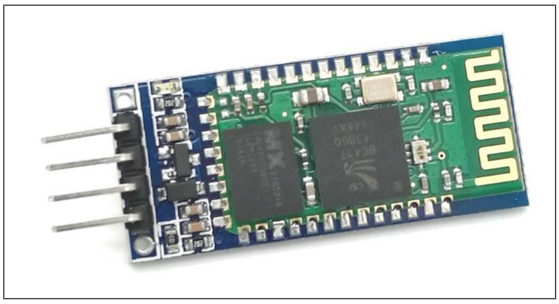

Figure B.8 Bluetooth module.

sensor cases from aluminum rods with a lathe. Then, the sensors were firmly placed within these cases. Preventing ambient noise interference was crucial to obtain high resolution and accuracy in both thermistor and thermopile signals. The aluminum cases act as a Faraday cage and prevent the sensors from picking up interferences. However, unshielded, long cables connecting the sensors to the amplification circuit can also pick up interferences. Therefore, I have decided to use HDMI cables to connect the sensors to the amplification stage. There were numerous HDMI cables in the market with different designs. I have specifically selected the HDMI cables with three layers of shielding (foil and braid). The sensors within their cases were shown with the orange box in Figure B.11. Amplification and ADC circuit was placed within a conductive metal box (shown with red in Figure B.11), which also acts as a Faraday cage and reduces ambient interference. The connection between the microcontroller and the amplification-digitization stage was also established with an HDMI cable to minimize the ambient interference (blue box in Figure B.11). The microcontroller (MSP430F5529) and battery (BOOSTXL-BATPAKMKII) were shown in the green

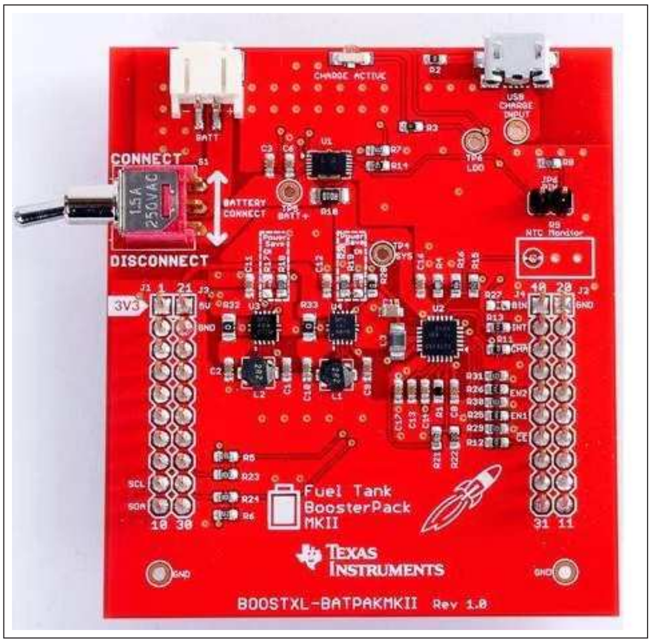

Figure B.9 Texas Instruments BOOSTXL-BATPAKMKII battery module.

box, while the Bluetooth module in the maroon box in Figure B.11.

The system produces numerical values range between 0 to 8388607 (i.e., 0 to $2^{23}-1$). The upper limit of the output value was determined by the fact that the LMP performs 24-bit analog-to-digital conversion for a range from -8388608 to 8388607. As the present design does not produce negative voltage values thanks to the 1.25 V voltage regulator used in the amplification stage, the number of bits used for digitization reduces by one, becoming 23 bits, which causes the upper limit to be 8388607. As a result, the system records four independent numerical values for each temperature reading cycle (two for thermistors and two for thermopiles). Thus, a calibration procedure is required to convert these numerical values into temperature values.

B.4 Changes and Updates in Sensor and Circuit Design

The Dexter ST60 sensors were discarded due to physical damage. The producer company told that the product has been discontinued. I have found an alternative sensor from the Heimann company. Thermopile sensor HMS Z11 is also equipped with

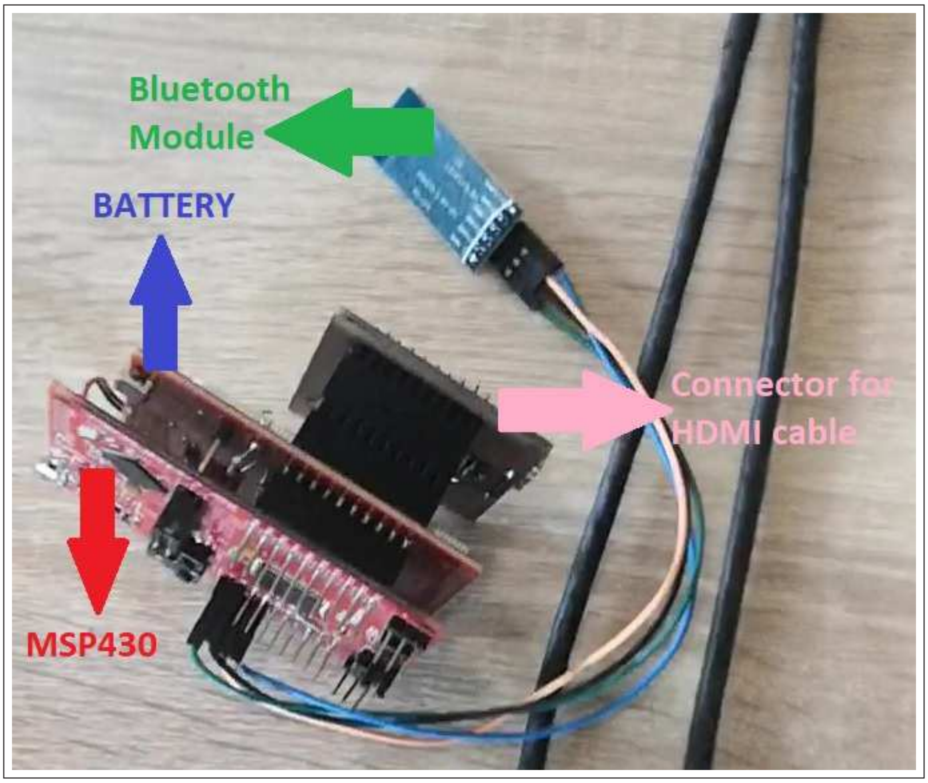

Figure B.10 The connected microcontroller and battery module.

a thermopile and a thermistor, which meant that it has the same working principle as Dexter sensors. Therefore, no fundamental changes were required in the system design. However, the difference between the two sensors was in the thermistor. Previous sensors (Dexter ST60) had a 25 kOHm NTC thermistor, while the new ones (HMS Z11) were equipped with a 100 kOhm NTC sensor. The system has been using 100 μA current to drive the thermistors. A relatively small current value was required to prevent the self-heating of the thermistor, which can lead to incorrect results. In the previous sensors, the thermistor output voltage values were within the appropriate range for the system. On the other hand, the new sensor's thermistor output voltage values were above the maximum voltage level allowed by LMP90100, therefore required to be reduced. To overcome this problem, I have added a 56 kOhm resistor in parallel to the thermistors.

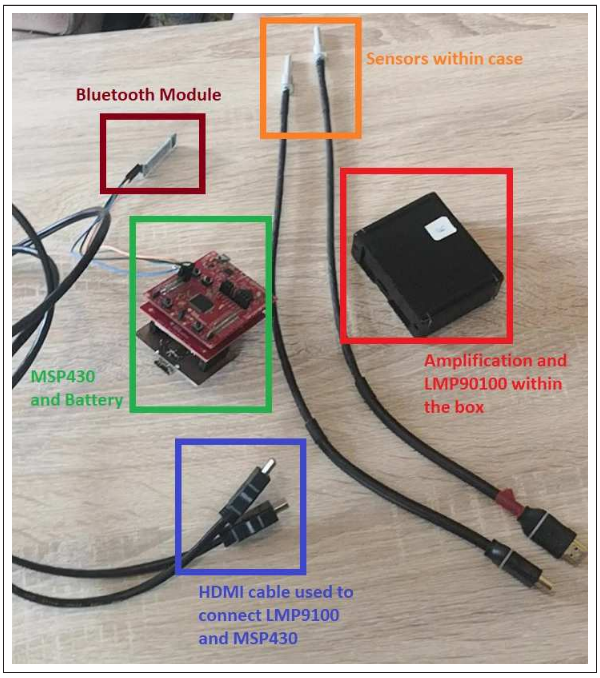

Figure B.11 Temperature measurement system with all parts.

B.5 Calibration and Performance

Each sensor was calibrated separately for its thermistor and thermopile. As the thermopile voltage output depends on the ambient (i.e., sensor) temperature, thermistors were calibrated as a first step. The procedures were explained in the following subsections.

B.5.1 Thermistor Calibration

<u>**System Overview.**</u>

Thermistor calibration was done via a custom-made system consisting of an adjustable rodent heater system and a digital temperature sensor. Adjustable rodent heater systems are used to stabilize the body temperature of the animal during surgeries. The system has a heater pad on which the animal is placed and a temperature sensor probe with which the body temperature of the animal can be measured. The device increase or decrease the heat depending on the feedback from the temperature sensor probe so that the heater pad's temperature is stabilized at a target temperature. Two aluminum sheets were cut and placed the heater pad between these aluminum sheets to obtain an evenly heated surface. A thermally conductive double-sided tape was used to attach the sensors to one of the aluminum sheets to increase the heat conduction. Subsequently, a commercial digital temperature sensor (DS18B20) was placed. This was the same sensor used in auditory experiments. Thus, it has the same specifications but with one difference: The sensors used in the TMT experiments had a waterproof metallic case, while the sensor used in the calibration procedure did not have a protective case, allowing it to be in contact with to be calibrated sensors. It was ensured that the sensors to be calibrated and DS18B20 were in contact with each other and the thermally conductive tape during the calibration procedure. Lastly, the temperature sensor probe of the system was attached to the aluminum sheet, which allowed monitoring and changing the thermal pad's temperature step by step throughout the calibration. This system was placed within a high-density foam box so that neither the heater system nor the sensors can be affected by the ambient temperature changes or small air currents.

Procedure.

The system was placed within the foam box and closed the lid. Then, the heater system was turned on, set the target temperature approximately at 29° C, and waited for approximately 30 minutes to allow the system and the sensors to reach thermal equilibrium. The resolution of the heater pad system was 0.1°C. Therefore, the actual temperature of the heater pad, aluminum sheet, and to be calibrated sensors were measured via the digital thermometer (i.e., DS18B20). The thermistor values were continuously recorded for one minute, during which the temperature recordings of DS18B20 were also stable. Then, the heater's target temperature was increased to the next temperature value and waited for thermal equilibrium. Twenty-four independent temperature recordings were done within the range of 28.81° C and 39.81° C with the steps of approximately 0.5° C. As a result, each sensor had a one-minute long thermistor output recording at 24 different temperature values.

Calculation, Modeling, and Formulation.

The sampling frequency of the system was approximately 101 Hz, which meant that there are roughly 6060 thermistor measurements for one-minute long recordings. An average thermistor output for each sensor at each calibration temperature was calculated. As a result, there were 24 temperature values (from DS18B20) and 24 numerical values (from ADC) of a thermistor. The curve fitting toolbox of MATLAB R2017B was used to compute the curve parameters. ADC output values were provided as the input, while the temperature values were converted in Kelvin and used as the output. The coefficients were calculated for the 3rd-degree polynomial equation for both sensors (Eq. B.1). R-square and adjusted R-square values were 1.

$$T_{thermistor} = p1 \times X^3 + p2 \times X^2 + p3 \times X + p4 \tag{B.1}$$

where $T_{thermistor}$ is the temperature of the sensor in Kelvin degree, X is the ADC output value of the thermistor, and p* values are the coefficients calculated by the MATLAB fitting tool. The fit can be seen in Figure B.12. The equation parameters were calculated for each sensor separately, as even a minor difference between sensors can result in incorrect temperature calculations.

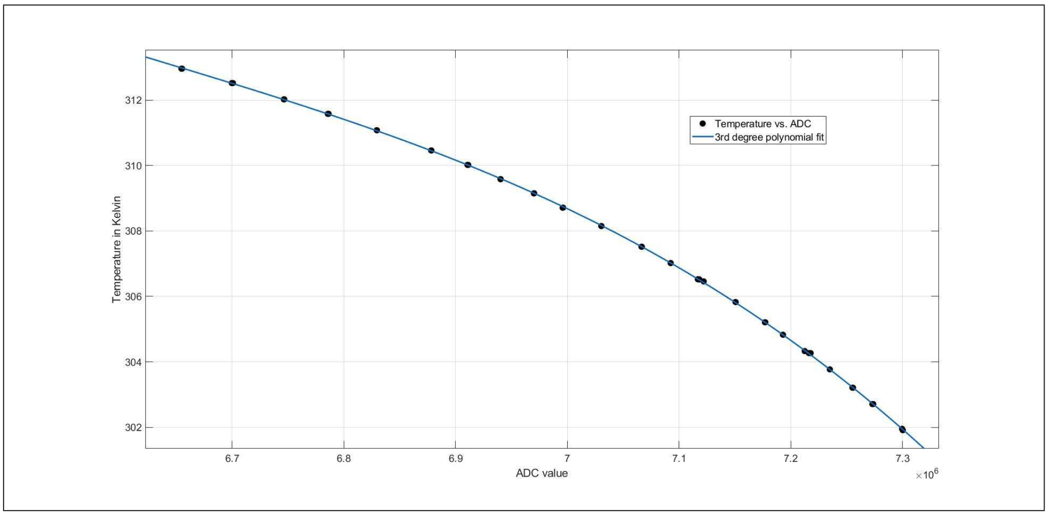

Figure B.12 Fitting curve of a thermistor.

B.5.2 Thermopile Calibration

<u>**System Overview.**</u>

Each sensor was calibrated separately. The calibration was done with a combination of various devices. Omega Engineering BB702 blackbody calibrator was used as a calibrator. The device can be seen in Figure B.13. The temperature of the black, round-shaped target plate of the device is controlled via control buttons and can be set at a range of 32° Celsius to 212° Celsius with 1° C steps. Moreover, the blackbody calibrator has a 100-ohm platinum RTD sensor (PT100) physically connected to the target plate, allowing to measure the target plateâs temperature with better accuracy. PT100 temperature sensor was connected to a high-performance digital multimeter (Keithley Instruments DM6500) for measurement. DM6500 device can measure resistance at a 50 Hz sampling rate and with a resolution of approximately 0.002 ohms, which corresponds approximately to 0.01° Celsius.

Figure B.13 Omega BB702 Blackbody Calibrator.

Lastly, a custom-made header was produced with a 3D printer (Figure B.14). This piece can fit into the target plate cavity, allowing to stabilize the sensors within the calibratorâs cavity at a certain distance from the target plate during the calibration. It should be noted that the center of the sensor was aligned with the center of the target plate. The other advantage of this header was that it prevented ambient conditions (e.g., air current, temperature changes, illumination changes, etc.) to affect the stability of the target plate temperature.

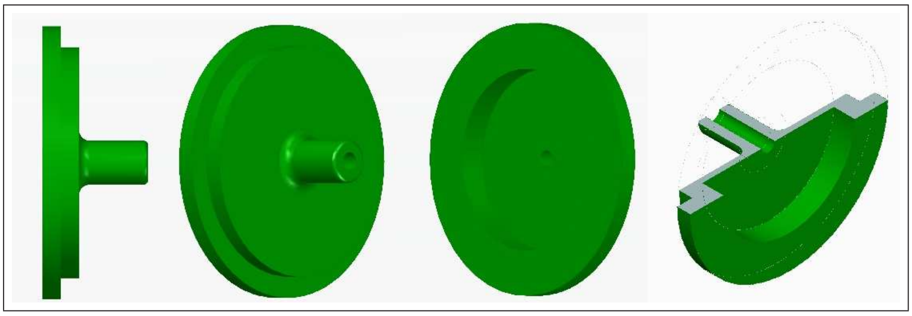

Figure B.14 Header for thermopile calibration from different angles.

Procedure.

After each piece of equipment was placed properly, the systems were turned on. The target temperature of BB702 was set at 35° Celsius and waited for an hour to allow for the sensor and the blackbody calibrator to reach thermal equilibrium. Then, 30 minutes long recordings were made for both thermopile output and the PT100 sensor. Subsequently, the target temperature was increased to 36°Celsius, followed by the same procedure. As the ear temperature was not expected to reach 38°Celsius and the thermopile producer company (Heimann) suggested a three-point calibration, the target temperature was increased to 37°Celsius as the last step, and the calibration steps have been repeated. The same procedure was done for the other sensor as well. As a result, there were 30-minutes long continuous measurements of thermopile output and PT100 output for both sensors.

Calculation, Modeling, and Formulation.

The producer company (Heimann) provided the following equation:

$$V_{obj} = K \times \epsilon \times (T_{obj}^4 - T_{amb}^4) \tag{B.2}$$

where V_{obj} is the voltage produced by the thermopile, K is the sensor constant, ϵ is the emissivity of the target object, T_{obj} is the temperature of the target object in Kelvin, and T_{amb} is the temperature of the ambient (i.e., sensor) temperature. It should be noted that the ambient (or sensor) temperature is the temperature measured by the thermistor. The main goal of the calibration was to find the K value from series of measurements performed at different target temperatures.

As stated above, the sampling rate of LMP90100 was approximately 101 Hz, while the PT100 measurement was sampled at 50 Hz. Therefore, data sizes were mismatched. Therefore, the thermopile data was downsampled in MATLAB as a first step. Even though the blackbody calibrator was a high-performance device, it had fluctuations in the target plate temperature measurements. Hence, the thermistor, thermopile, and PT100 recordings were simultaneously checked to manually identify the most stable epochs across them for each target temperature value (i.e., 36°, 37°, 38° C). These epochs were used in calculating the K value. To sum, tens of K values by using V_{obj}, T_{obj}, and T_{amb} measurements for a sensor were computed. Then, I have calculated the average of these values to obtain the final K value for a sensor. K value was calculated for each sensor independently.

Lastly, the following equation was used for calculating the target temperature:

$$T_{obj} = \sqrt[4]{\frac{V_{obj}}{K \times \epsilon} + T_{amb}^4} \tag{B.3}$$

B.5.3 Code, Example Screen, and Performance

Obtaining the actual target temperature from ADC outputs requires 3^{rd} order polynomial and 4^{th} order root calculations. These calculations could be done with the microcontroller at the expense of the sampling rate. Therefore, complex mathematical calculations were performed in MATLAB after collecting the raw data from the microcontroller via Bluetooth. The whole code was provided in Appendix B.6. The Bluetooth identity of the TMT system was defined as the first step, followed by the definition of the various parameters and coefficients. Subsequently, the connection is established with the TMT system, and the user was asked to hit the 'Enter' to start the measurement. Four raw data (two thermopiles and two thermistors) were collected. Moving average filter with a window of 20 data points was used to filter the raw data to increase the signal-to-noise ratio. Then, the ambient temperature was calculated for each sensor, then the target (i.e., ear membrane) temperature was calculated. Each recording was presented on the screen with a timestamp. An example of a screen can be seen in Figure B.15. The recording can be stopped at any time by pressing 'e' from the keyboard.

Performance.

The overall system has a sampling rate of 101 Hz. To identify the noise level in both thermistor and thermopile measurements, I have placed the sensors within a foam box and left them in there overnight so that they could reach thermal equilibrium. Subsequently, I collected data for 5 minutes. It should be expected that the fluctuations seen in the ADC output were originated from the electronic components of the system. Example signals of thermistor and thermopile can be seen in Figure B.16. As there was no baseline shift in the original recordings, time series were detrended so that the baseline level became zero.

The standard deviation of the thermistor time series was 365, while it was 351 for the thermopile time series. As a next step, I have created a data set consisting

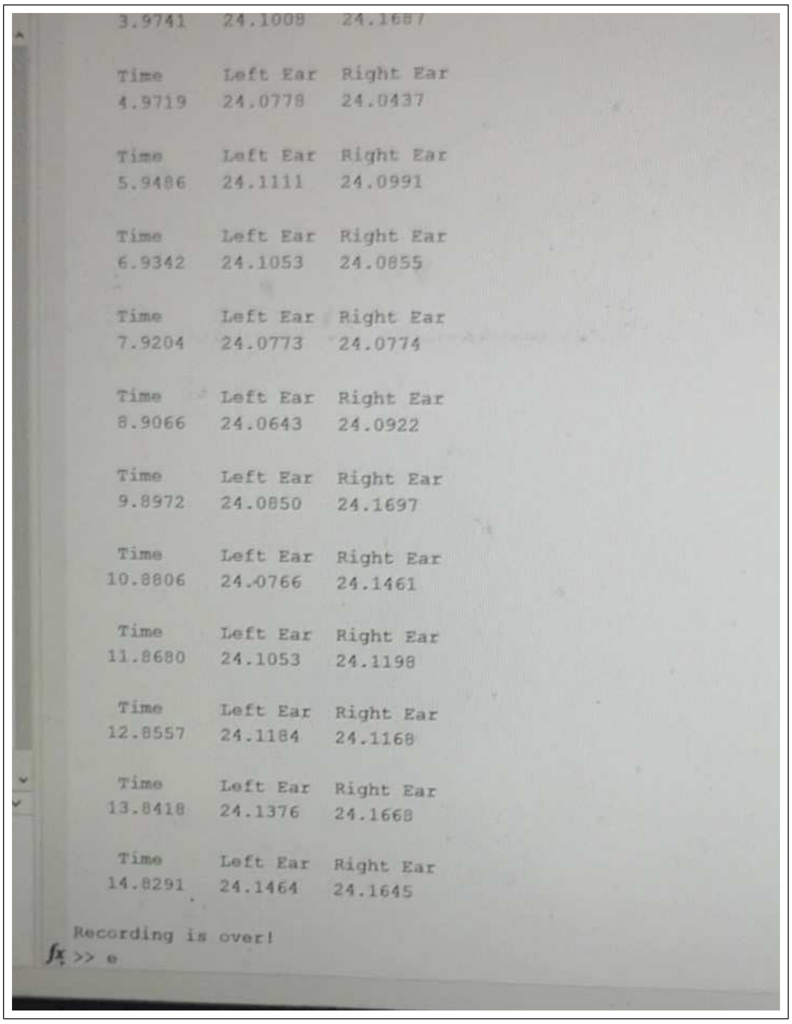

Figure B.15 An example recording screen.

of 100 ADC values (corresponding approximately to 35° Celsius) with increments of 365 and calculated the temperature with the thermistor Eq. B.1. Subsequently, the temperature increase between each adjacent step was calculated. The average temperature increase (or decrease) between the two adjacent data points for the thermistor was 0.0061° Celsius. similar calculations were done for thermopile time series (i.e., target temperature) based on Eq. B.3 and found that the standard deviation of 351 corresponds to 0.0021° Celsius. The fluctuations of 0.0061° Celsius and 0.0021° Celsius could not be summed to find the total noise of the system, as the equations involve non-linear elements. The temperature deviation from an ideal state was calculated for two extreme conditions: 1. Thermistor minus one standard deviation/thermopile minus one standard deviation 2. Thermistor plus one standard deviation/thermopile

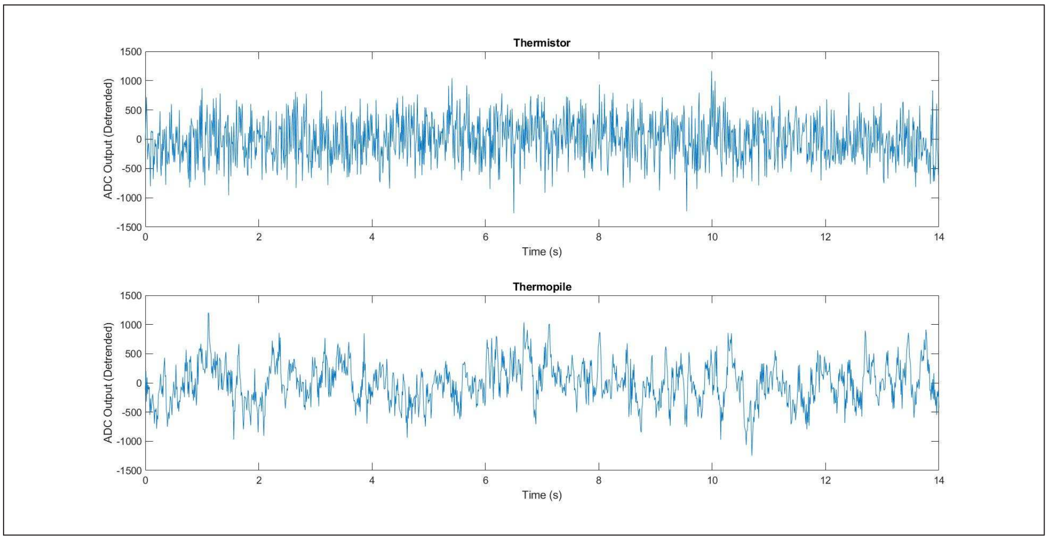

Figure B.16 Thermistor and thermopile time series example.

plus one standard deviation. In the first condition, the measured temperature was 0.0081° Celsius lower than the actual temperature, while the measured temperature was 0.0081° Celsius higher than the actual temperature in the second condition. These values were lower than the initial goal of 0.01° Celsius resolution. All these calculations were made based on the raw, unfiltered time series of thermistor and thermopile. However, it should be noted that the system implements filtering. A moving average filter with a window size of 20 data points (i.e., approximately 200 ms) was applied. The standard deviation of thermistor and thermopile was reduced to 91 and 215, respectively. Accordingly, the temperature fluctuations were reduced to 0.0015° Celsius and 0.0013° Celsius for thermistor and thermopile, respectively. Lastly, the combined effect of one standard deviation in both thermopile and thermistor signals was calculated. The difference from the actual temperature was 0.0030°Celsius, which was also smaller than the initial goal of 0.01° Celsius resolution.

B.6 MATLAB Script for Data Collection and Temperature Calculation

```
clc
clear B_data
```

```
if exist('bt1')==1
    disp('Object is ready to connect!')
else
    bt1=Bluetooth('Tympanic_Therm',1)
end
h_fig = figure;

load KforL
load KforR

load leftcoeff
pl1 = pl(1);
pl2 = pl(2);
pl3 = pl(3);
pl4 = pl(4);
load rightcoeff
pr1 = pr(1);
pr2 = pr(2);
pr3 = pr(3);
pr4 = pr(4);

offset = 3163125; %vref ADC value

m=1;
t=1;
s=1;
a=1;

fclose(bt1)
fopen(bt1)
```

```
control=1
LEar=nan(100000,1);
REar=nan(100000,1);
A=['      Time        Left Ear    Right Ear'];

disp('Press Enter to Start Recording')
pause;
fwrite(bt1,'1') % start reading
tic
while 1
    B_data=fscanf(bt1,'%d %d %d %d');% data
    if a==1
        clear B_data
        a=2;
        continue
    elseif isempty(B_data)
        continue
    else

    %fetch raw data
    L(s,1:2)=transpose(B_data(1:2,1));
    R(s,1:2)=transpose(B_data(3:4,1));

    if mod(s,100)==0
        q=s/100;
    %calculate average thermistor
    x=nanmean(L((q-1)*100+1:q*100,1))/2^23;
    LTerm=pl1*x.^3 + pl2*x.^2 + pl3*x + pl4;
    y=nanmean(R((q-1)*100+1:q*100,1))/2^23;
    RTerm=pr1*y.^3 + pr2*y.^2 + pr3*y + pr4;
```

```

    % calculate ear temp
    Ltemp=(nthroot((((nanmean(L((q-1)*100+1:q*100,2))-offset)/
        LK)+LTerm^4),4));
    Ltemp=convtemp(Ltemp,'K','C');
    LEar(q)=Ltemp;

    Rtemp=(nthroot((((nanmean(R((q-1)*100+1:q*100,2))-offset)/
        RK)+RTerm^4),4));
    Rtemp=convtemp(Rtemp,'K','C');
    REar(q)=Rtemp;
    t(q)=toc;
        B=[t(q) Ltemp, Rtemp];
        disp(A)
        disp(B)
    end
    s=s+1;
    end


drawnow
st=get(h_fig,'CurrentCharacter');
isKeyPressed = ~isempty(get(h_fig,'CurrentCharacter'));
if st=='e'
    close all
break
end

end

fwrite(bt1,'0') % stop reading
```

```
fclose(bt1)
disp('Recording is over!')
```

REFERENCES

1. Lin, K., G. Moonis, and L. R. Lustig, "Mastoiditis," in *Infections of the Ears, Nose, Throat, and Sinuses*, pp. 67–78, Springer International Publishing, 2018.

2. Leon-Carrion, J., and U. Leon-Dominguez, "Functional near-infrared spectroscopy (fNIRS): Principles and neuroscientific applications," in *Neuroimaging - Methods*, InTech, 2012.

3. Pinti, P., I. Tachtsidis, A. Hamilton, J. Hirsch, C. Aichelburg, S. Gilbert, and P. W. Burgess, "The present and future use of functional near-infrared spectroscopy (fNIRS) for cognitive neuroscience," *Annals of the New York Academy of Sciences*, Vol. 1464, no. 1, pp. 5–29, 2020.

4. Marois, R., and J. Ivanoff, "Capacity limits of information processing in the brain," *Trends in Cognitive Sciences*, Vol. 9, no. 6, pp. 296–305, 2005.

5. Frost, J. A., "Language processing is strongly left lateralized in both sexes: Evidence from functional MRI," *Brain*, Vol. 122, no. 2, pp. 199–208, 1999.

6. Scholkmann, F., M. Wolf, and U. Wolf, "The effect of inner speech on arterial CO2 and cerebral hemodynamics and oxygenation: A functional NIRS study," in *Oxygen Transport to Tissue XXXV*, pp. 81–87, Springer New York, 2013.

7. Greenhill, S. J., Q. D. Atkinson, A. Meade, and R. D. Gray, "The shape and tempo of language evolution," *Proceedings of the Royal Society B: Biological Sciences*, Vol. 277, no. 1693, pp. 2443–2450, 2010.

8. Kandler, A., and J. Steele, "Modeling language shift," *Proceedings of the National Academy of Sciences of the United States of America*, Vol. 114, no. 19, pp. 4851–4853, 2017.

9. Laughlin, S. B., R. R. de Ruyter van Steveninck, and J. C. Anderson, "The metabolic cost of neural information," *Nature Neuroscience*, Vol. 1, no. 1, pp. 36–41, 1998.

10. Raichle, M. E., and D. A. Gusnard, "Appraising the brains energy budget," *Proceedings of the National Academy of Sciences*, Vol. 99, no. 16, pp. 10237–10239, 2002.

11. Mrozek, S., F. Vardon, and T. Geeraerts, "Brain temperature: Physiology and pathophysiology after brain injury," *Anesthesiology Research and Practice*, Vol. 2012, pp. 1–13, 2012.

12. Kiyatkin, E. A., "Brain temperature homeostasis: physiological fluctuations and pathological shifts," *Frontiers in Bioscience*, Vol. 15, no. 1, p. 73, 2010.

13. Holt, W. R., and E. C. Brainard, "Selective hyperthermia and reaction time," *Perceptual and Motor Skills*, Vol. 43, no. 2, pp. 375–382, 1976.

14. Hancock, P. A., and G. R. Dirkin, "Central and peripheral visual choice-reaction time under conditions of induced cortical hyperthermia," *Perceptual and Motor Skills*, Vol. 54, no. 2, pp. 395–402, 1982.

15. Gaoua, N., S. Racinais, J. Grantham, and F. E. Massioui, "Alterations in cognitive performance during passive hyperthermia are task dependent," *International Journal of Hyperthermia*, Vol. 27, no. 1, pp. 1–9, 2010.

16. Kiyatkin, E. A., P. L. Brown, and R. A. Wise, "Brain temperature fluctuation: a reflection of functional neural activation," *European Journal of Neuroscience*, Vol. 16, no. 1, pp. 164–168, 2002.

17. Helton, W. S., R. P. Kern, and D. R. Walker, "Tympanic membrane temperature, exposure to emotional stimuli and the sustained attention to response task," *Journal of Clinical and Experimental Neuropsychology*, Vol. 31, no. 5, pp. 611–616, 2009.

18. Sukstanskii, A. L., and D. A. Yablonskiy, "Theoretical model of temperature regulation in the brain during changes in functional activity," *Proceedings of the National Academy of Sciences*, Vol. 103, no. 32, pp. 12144–12149, 2006.

19. Hirnstein, M., S. Leask, J. Rose, and M. Hausmann, "Disentangling the relationship between hemispheric asymmetry and cognitive performance," *Brain and Cognition*, Vol. 73, no. 2, pp. 119–127, 2010.

20. Kimura, D., "From ear to brain," *Brain and Cognition*, Vol. 76, no. 2, pp. 214–217, 2011.

21. Herff, C., D. Heger, F. Putze, J. Hennrich, O. Fortmann, and T. Schultz, "Classification of mental tasks in the prefrontal cortex using fNIRS," in *2013 35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, IEEE, 2013.

22. Helton, W. S., and M. Maginnity, "Increased attentiveness is associated with hemispheric asymmetry measured with lateral tympanic membrane temperature in humans and dogs," *Experimental Brain Research*, Vol. 219, no. 3, pp. 321–326, 2012.

23. Papo, D., "Measuring brain temperature without a thermometer," *Frontiers in Physiology*, Vol. 5, 2014.

24. Parr, L., and W. Hopkins, "Brain temperature asymmetries and emotional perception in chimpanzees, pan troglodytes," *Physiology & Behavior*, Vol. 71, no. 3-4, pp. 363–371, 2000.

25. Cherbuin, N., and C. Brinkman, "Cognition is cool: Can hemispheric activation be assessed by tympanic membrane thermometry?," *Brain and Cognition*, Vol. 54, no. 3, pp. 228–231, 2004.

26. Jackson, C. J., "Evidence of a relationship between asymmetries in tympanic membrane temperature and lateralised sensory preferences," *Laterality: Asymmetries of Body, Brain and Cognition*, Vol. 16, no. 1, pp. 107–124, 2011.

27. Propper, R. E., and T. T. Brunyé, "Lateralized difference in tympanic membrane temperature: Emotion and hemispheric activity," *Frontiers in Psychology*, Vol. 4, 2013.

28. Stone, J. G., R. R. Goodman, K. Z. Baker, C. J. Baker, and R. A. Solomon, "Direct intraoperative measurement of human brain temperature," *Neurosurgery*, Vol. 41, no. 1, pp. 20–24, 1997.

29. Maloney, S. K., A. Fuller, G. Mitchell, and D. Mitchell, "Rectal temperature measurement results in artifactual evidence of selective brain cooling," *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, Vol. 281, no. 1, pp. R108–R114, 2001.

30. Webb, G. E., "Comparison of esophageal and tympanic temperature monitoring during cardiopulmonary bypass," *Anesthesia & Analgesia*, Vol. 52, no. 5, p. 729???733, 1973.

31. Shevelev, I. A., "Temperature topography of the brain cortex: Thermoencephaloscopy," *Brain Topography*, Vol. 5, no. 2, pp. 77–85, 1992.

32. Benzinger, T. H., "Heat regulation: homeostasis of central temperature in man," *Physiological Reviews*, Vol. 49, no. 4, pp. 671–759, 1969.

33. Meiners, M. L., and J. M. Dabbs, "Ear temperature and brain blood flow: Laterality effects," *Bulletin of the Psychonomic Society*, Vol. 10, no. 3, pp. 194–196, 1977.

34. Swift, A. B., and M. B. Perlman, "A noninvasive index of hemispheric activity," *Perceptual and Motor Skills*, Vol. 60, no. 2, pp. 515–524, 1985.

35. Swift, A. B., "Tympanic thermometry: An index of hemispheric activity," *Perceptual and Motor Skills*, Vol. 73, no. 1, pp. 275–293, 1991.

36. Hopkins, W. D., and L. A. Fowler, "Lateralized changes in tympanic membrane temperature in relation to different cognitive tasks in chimpanzees (pan troglodytes).," *Behavioral Neuroscience*, Vol. 112, no. 1, pp. 83–88, 1998.

37. Cherbuin, N., and C. Brinkman, "Sensitivity of functional tympanic membrane thermometry (fTMT) as an index of hemispheric activation in cognition," *Laterality: Asymmetries of Body, Brain and Cognition*, Vol. 12, no. 3, pp. 239–261, 2007.

38. Hansen, J. T., and F. H. Netter, *Netter's Clinical Anatomy*, Philadelphia, USA: Elsevier, 4th ed., 2019.

39. Mariak, Z., M. D. White, T. Lyson, and J. Lewko, "Tympanic temperature reflects intracranial temperature changes in humans," *Pflügers Archiv - European Journal of Physiology*, Vol. 446, no. 2, pp. 279–284, 2003.

40. Schuhmann, M. U., D. F. Suhr, H.-H. v. Gösseln, A. Bräuer, J.-P. Jantzen, and M. Samii, "Local brain surface temperature compared to temperatures measured at standard extracranial monitoring sites during," *Journal of Neurosurgical Anesthesiology*, Vol. 11, no. 2, pp. 90–95, 1999.

41. Helton, W. S., "The relationship between lateral differences in tympanic membrane temperature and behavioral impulsivity," *Brain and Cognition*, Vol. 74, no. 2, pp. 75–78, 2010.

42. Genovese, J. E. C., K. E. Sparks, and K. D. Little, "Tympanic membrane temperature and hemispheric cognitive style," *The Journal of Genetic Psychology*, Vol. 178, no. 5, pp. 298–302, 2017.

43. Lorr, D., A. Lund, M. Fredrikson, and N. H. Secher, "Tympanic membrane temperature decreases during head up tilt: relation to frontal lobe oxygenation and middle cerebral artery mean blood flow velocity," *Scandinavian Journal of Clinical and Laboratory Investigation*, Vol. 77, no. 8, pp. 587–591, 2017.

44. Scholkmann, F., S. Kleiser, A. J. Metz, R. Zimmermann, J. M. Pavia, U. Wolf, and M. Wolf, "A review on continuous wave functional near-infrared spectroscopy and imaging instrumentation and methodology," *NeuroImage*, Vol. 85, pp. 6–27, 2014.

45. Herold, F., P. Wiegel, F. Scholkmann, and N. Müller, "Applications of functional near-infrared spectroscopy (fNIRS) neuroimaging in exercise–cognition science: A systematic, methodology-focused review," *Journal of Clinical Medicine*, Vol. 7, no. 12, p. 466, 2018.

46. Ferrari, M., and V. Quaresima, "A brief review on the history of human functional near-infrared spectroscopy (fNIRS) development and fields of application," *NeuroImage*, Vol. 63, no. 2, pp. 921–935, 2012.

47. Curtin, A., J. Sun, Q. Zhao, B. Onaral, J. Wang, S. Tong, and H. Ayaz, "Visuospatial task-related prefrontal activity is correlated with negative symptoms in schizophrenia," *Scientific Reports*, Vol. 9, no. 1, 2019.

48. Ji, X., W. Quan, L. Yang, J. Chen, J. Wang, and T. Wu, "Classification of schizophrenia by seed-based functional connectivity using prefronto-temporal functional near infrared spectroscopy," *Journal of Neuroscience Methods*, Vol. 344, p. 108874, 2020.

49. Akın, A., D. Bilensoy, U. E. Emir, M. Gülsoy, S. Candansayar, and H. Bolay, "Cerebrovascular dynamics in patients with migraine: Near-infrared spectroscopy study," *Neuroscience Letters*, Vol. 400, no. 1-2, pp. 86–91, 2006.

50. Banville, H., R. Gupta, and T. H. Falk, "Mental task evaluation for hybrid NIRS-EEG brain-computer interfaces," *Computational Intelligence and Neuroscience*, Vol. 2017, pp. 1–24, 2017.

51. Qureshi, N. K., N. Naseer, F. M. Noori, H. Nazeer, R. A. Khan, and S. Saleem, "Enhancing classification performance of functional near-infrared spectroscopy- brain–computer interface using adaptive estimation of general linear model coefficients," *Frontiers in Neurorobotics*, Vol. 11, 2017.

52. Jasinska, K., and L. Petitto, "How age of bilingual exposure can change the neural systems for language in the developing brain: A functional near infrared spectroscopy investigation of syntactic processing in monolingual and bilingual children," *Developmental Cognitive Neuroscience*, Vol. 6, pp. 87–101, 2013.

53. Sugiura, L., S. Ojima, H. Matsuba-Kurita, I. Dan, D. Tsuzuki, T. Katura, and H. Hagiwara, "Effects of sex and proficiency in second language processing as revealed by a large-scale fNIRS study of school-aged children," *Human Brain Mapping*, Vol. 36, no. 10, pp. 3890–3911, 2015.

54. Fu, G., N. J. A. Wan, J. M. Baker, J. W. Montgomery, J. L. Evans, and R. B. Gillam, "A proof of concept study of function-based statistical analysis of fNIRS data: Syntax comprehension in children with specific language impairment compared to typically-developing controls," *Frontiers in Behavioral Neuroscience*, Vol. 10, 2016.

55. Baker, J. M., J. L. Bruno, A. Gundran, S. M. H. Hosseini, and A. L. Reiss, "Correction: fNIRS measurement of cortical activation and functional connectivity during a visuospatial working memory task," *PLOS ONE*, Vol. 13, no. 8, p. e0203233, 2018.

56. Artemenko, C., A. Coldea, M. Soltanlou, T. Dresler, H.-C. Nuerk, and A.-C. Ehlis, "The neural circuits of number and letter copying: an fNIRS study," *Experimental Brain Research*, Vol. 236, no. 4, pp. 1129–1138, 2018.

57. Lucas, I., P. Urieta, F. Balada, E. Blanco, and A. Aluja, "Differences in prefrontal cortex activity based on difficulty in a working memory task using near-infrared spectroscopy," *Behavioural Brain Research*, Vol. 392, p. 112722, 2020.

58. Yamazaki, H., Y. Kanazawa, and K. Omori, "Advantages of double density alignment of fNIRS optodes to evaluate cortical activities related to phonological short-term memory using NIRS-SPM," *Hearing Research*, Vol. 395, p. 108024, 2020.

59. Brenders, P., J. G. van Hell, and T. Dijkstra, "Word recognition in child second language learners: Evidence from cognates and false friends," *Journal of Experimental Child Psychology*, Vol. 109, no. 4, pp. 383–396, 2011.

60. Dijkstra, T., E. D. Bruijn, H. Schriefers, and S. T. Brinke, "More on interlingual homograph recognition: language intermixing versus explicitness of instruction," *Bilingualism: Language and Cognition*, Vol. 3, no. 1, pp. 69–78, 2000.

61. Schulpen, B., T. Dijkstra, H. J. Schriefers, and M. Hasper, "Recognition of interlingual homophones in bilingual auditory word recognition.," *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 29, no. 6, pp. 1155–1178, 2003.

62. von Studnitz, R. E., and D. W. Green, "Interlingual homograph interference in german–english bilinguals: Its modulation and locus of control," *Bilingualism: Language and Cognition*, Vol. 5, no. 01, 2002.

63. Chen, P., S. C. Bobb, N. Hoshino, and V. Marian, "Neural signatures of language co-activation and control in bilingual spoken word comprehension," *Brain Research*, Vol. 1665, pp. 50–64, 2017.

64. Acheson, D. J., L. Y. Ganushchak, I. K. Christoffels, and P. Hagoort, "Conflict monitoring in speech production: Physiological evidence from bilingual picture naming," *Brain and Language*, Vol. 123, no. 2, pp. 131–136, 2012.

65. Broersma, M., D. Carter, and D. J. Acheson, "Cognate costs in bilingual speech production: Evidence from language switching," *Frontiers in Psychology*, Vol. 7, 2016.

66. Caramazza, A., A. Costa, M. Miozzo, and Y. Bi, "The specific-word frequency effect: Implications for the representation of homophones in speech production.," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, Vol. 27, no. 6, pp. 1430–1450, 2001.

67. Jescheniak, J. D., and W. J. M. Levelt, "Word frequency effects in speech production: Retrieval of syntactic information and of phonological form.," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, Vol. 20, no. 4, pp. 824–843, 1994.

68. Carrasco-Ortiz, H., K. J. Midgley, and C. Frenck-Mestre, "Are phonological representations in bilinguals language specific? an ERP study on interlingual homophones," *Psychophysiology*, Vol. 49, no. 4, pp. 531–543, 2012.

69. Lagrou, E., R. J. Hartsuiker, and W. Duyck, "Knowledge of a second language influences auditory word recognition in the native language.," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, Vol. 37, no. 4, pp. 952–965, 2011.

70. Wang, X., B. Hui, and S. Chen, "Language selective or non-selective in bilingual lexical access? it depends on lexical tones!," *PLOS ONE*, Vol. 15, no. 3, p. e0230412, 2020.

71. Schröter, P., and S. Schroeder, "Orthographic processing in balanced bilingual children: Cross-language evidence from cognates and false friends," *Journal of Experimental Child Psychology*, Vol. 141, pp. 239–246, 2016.

72. van Hell, J. G., and D. Tanner, "Second language proficiency and cross-language lexical activation," *Language Learning*, Vol. 62, pp. 148–171, 2012.

73. van Heuven, W. J., H. Schriefers, T. Dijkstra, and P. Hagoort, "Language conflict in the bilingual brain," *Cerebral Cortex*, Vol. 18, no. 11, pp. 2706–2716, 2008.

74. Brysbaert, M., G. Van Dyck, and M. Van De Poel, “Visual word recognition in bilinguals: Evidence from masked phonological priming,” *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 25, no. 1, pp. 137–148, 1999.

75. Lemhöfer, K., and T. Dijkstra, “Recognizing cognates and interlingual homographs: Effects of code similarity in language-specific and generalized lexical decision,” *Memory & Cognition*, Vol. 32, no. 4, pp. 533–550, 2004.

76. Dijkstra, T., J. Grainger, and W. J. van Heuven, “Recognition of cognates and interlingual homographs: The neglected role of phonology,” *Journal of Memory and Language*, Vol. 41, no. 4, pp. 496–518, 1999.

77. Friesen, D. C., and D. Jared, “Cross-language phonological activation of meaning: evidence from category verification,” *Bilingualism: Language and Cognition*, Vol. 15, no. 1, pp. 145–156, 2011.

78. Oğuz, P., and G. Ertaş, “Wireless dual channel human body temperature measurement device,” in *2013 International Conference on Electronics, Computer and Computation (ICECCO)*, IEEE, 2013.

79. Stroobant, N., and G. Vingerhoets, “Transcranial doppler ultrasonography monitoring of cerebral hemodynamics during performance of cognitive tasks: A review,” *Neuropsychology Review*, Vol. 10, no. 4, pp. 213–231, 2000.

80. Kimura, D., “The asymmetry of the human brain,” *Scientific American*, Vol. 228, no. 3, pp. 70–78, 1973.

81. Brysbaert, M., P. Mandera, and E. Keuleers, “The word frequency effect in word processing: An updated review,” *Current Directions in Psychological Science*, Vol. 27, no. 1, pp. 45–50, 2017.

82. Gardner, M. K., E. Z. Rothkopf, R. Lapan, and T. Lafferty, “The word frequency effect in lexical decision: Finding a frequency-based component,” *Memory & Cognition*, Vol. 15, no. 1, pp. 24–28, 1987.

83. Malmberg, K. J., and T. O. Nelson, “The word frequency effect for recognition memory and the elevated-attention hypothesis,” *Memory & Cognition*, Vol. 31, no. 1, pp. 35–43, 2003.

84. İlyas Göz, *Yazılı Türkçe'nin Kelime Sıklığı Sözlüğü*, TDK, 2003.

85. Tekcan, A., and İlyas Göz, *Türkçe Kelime Normları*, Boğaziçi Üniversitesi Yayınevi, 2005.

86. Leech, G., P. Rayson, and A. Wilson, *Word Frequencies in Written and Spoken English Based on the British National Corpus*, Routledge, 2014.

87. Washburn, D. A., and R. Putney, “Attention and task difficulty: When is performance facilitated?,” *Learning and Motivation*, Vol. 32, no. 1, pp. 36–47, 2001.

88. Pretz, J. E., and C. Zimmerman, “When the goal gets in the way: The interaction of goal specificity and task difficulty,” *Thinking & Reasoning*, Vol. 15, no. 4, pp. 405–430, 2009.

89. Kim, Y., J. Woo, and M. Woo, “Effects of stress and task difficulty on working memory and cortical networking,” *Perceptual and Motor Skills*, Vol. 124, no. 6, pp. 1194–1210, 2017.

90. Chevrier, A. D., M. D. Noseworthy, and R. Schachar, "Dissociation of response inhibition and performance monitoring in the stop signal task using event-related fMRI," *Human Brain Mapping*, Vol. 28, no. 12, pp. 1347–1358, 2007.

91. Simmonds, D. J., J. J. Pekar, and S. H. Mostofsky, "Meta-analysis of go/no-go tasks demonstrating that fMRI activation associated with response inhibition is task-dependent," *Neuropsychologia*, Vol. 46, no. 1, pp. 224–232, 2008.

92. Grosjean, F., "Spoken word recognition processes and the gating paradigm," *Perception & Psychophysics*, Vol. 28, no. 4, pp. 267–283, 1980.

93. Metsala, J. L., "An examination of word frequency and neighborhood density in the development of spoken-word recognition," *Memory & Cognition*, Vol. 25, no. 1, pp. 47–56, 1997.

94. Mainela-Arnold, E., J. L. Evans, and J. Coady, "Beyond capacity limitations II: Effects of lexical processes on word recall in verbal working memory tasks in children with and without specific language impairment," *Journal of Speech, Language, and Hearing Research*, Vol. 53, no. 6, pp. 1656–1672, 2010.

95. Berglund-Barraza, A., F. Tian, C. Basak, and J. L. Evans, "Word frequency is associated with cognitive effort during verbal working memory: A functional near infrared spectroscopy (fNIRS) study," *Frontiers in Human Neuroscience*, Vol. 13, 2019.

96. Marian, V., J. Bartolotti, S. Rochanavibhata, K. Bradley, and A. E. Hernandez, "Bilingual cortical control of between- and within-language competition," *Scientific Reports*, Vol. 7, no. 1, 2017.

97. Sulpizio, S., N. D. Maschio, D. Fedeli, and J. Abutalebi, "Bilingual language processing: A meta-analysis of functional neuroimaging studies," *Neuroscience & Biobehavioral Reviews*, Vol. 108, pp. 834–853, 2020.

98. Kovelman, I., M. H. Shalinsky, M. S. Berens, and L.-A. Petitto, "Shining new light on the brains "bilingual signature": A functional near infrared spectroscopy investigation of semantic processing," *NeuroImage*, Vol. 39, no. 3, pp. 1457–1471, 2008.

99. Oi, M., H. Saito, H. Ito, and P. L. Rumme, "Semantic judgment of chinese–japanese bilinguals: a near-infrared spectroscopy study," *NeuroReport*, Vol. 21, no. 2, pp. 127–131, 2010.

100. Sugiura, L., S. Ojima, H. Matsuba-Kurita, I. Dan, D. Tsuzuki, T. Katura, and H. Hagiwara, "Sound to language: Different cortical processing for first and second languages in elementary school children as revealed by a large-scale study using fNIRS," *Cerebral Cortex*, Vol. 21, no. 10, pp. 2374–2393, 2011.

101. Fishburn, F. A., M. E. Norr, A. V. Medvedev, and C. J. Vaidya, "Sensitivity of fNIRS to cognitive state and load," *Frontiers in Human Neuroscience*, Vol. 8, 2014.

102. Amiri, M., P. Pouliot, C. Bonnéry, P.-O. Leclerc, M. Desjardins, F. Lesage, and Y. Joanette, "An exploration of the effect of hemodynamic changes due to normal aging on the fNIRS response to semantic processing of words," *Frontiers in Neurology*, Vol. 5, 2014.

103. Arredondo, M. M., X.-S. Hu, T. Satterfield, A. T. Riobóo, S. A. Gelman, and I. Kovelman, "Bilingual effects on lexical selection: A neurodevelopmental perspective," *Brain and Language*, Vol. 195, p. 104640, 2019.

104. Huppert, T. J., S. G. Diamond, M. A. Franceschini, and D. A. Boas, "HomER: a review of time-series analysis methods for near-infrared spectroscopy of the brain," *Applied Optics*, Vol. 48, no. 10, p. D280, 2009.

105. Hocke, L., I. Oni, C. Duszynski, A. Corrigan, B. Frederick, and J. Dunn, "Automated processing of fNIRS data—a visual guide to the pitfalls and consequences," *Algorithms*, Vol. 11, no. 5, p. 67, 2018.

106. Pfeifer, M. D., F. Scholkmann, and R. Labruyère, "Signal processing in functional near-infrared spectroscopy (fNIRS): Methodological differences lead to different statistical results," *Frontiers in Human Neuroscience*, Vol. 11, 2018.

107. Watanabe, A., N. Kato, and T. Kato, "Effects of creatine on mental fatigue and cerebral hemoglobin oxygenation," *Neuroscience Research*, Vol. 42, no. 4, pp. 279–285, 2002.

108. Dravida, S., J. A. Noah, X. Zhang, and J. Hirsch, "Comparison of oxyhemoglobin and deoxyhemoglobin signal reliability with and without global mean removal for digit manipulation motor tasks," *Neurophotonics*, Vol. 5, no. 01, p. 1, 2017.

109. de Roever, I., G. Bale, S. Mitra, J. Meek, N. J. Robertson, and I. Tachtsidis, "Investigation of the pattern of the hemodynamic response as measured by functional near-infrared spectroscopy (fnirs) studies in newborns, less than a month old: A systematic review," *Frontiers in Human Neuroscience*, Vol. 12, p. 371, 2018.

110. Voss, M. W., "Chapter 9 - the chronic exerciseâcognition interaction: fmri research," in *Exercise-Cognition Interaction* (McMorris, T., ed.), pp. 187–209, San Diego: Academic Press, 2016.

111. Elmer, S., "Broca pars triangularis constitutes a "hub" of the language-control network during simultaneous language translation," *Frontiers in Human Neuroscience*, Vol. 10, 2016.

112. Heim, S., B. Opitz, K. Müller, and A. Friederici, "Phonological processing during language production: fMRI evidence for a shared production-comprehension network," *Cognitive Brain Research*, Vol. 16, no. 2, pp. 285–296, 2003.

113. Moro, S. B., S. Cutini, M. L. Ursini, M. Ferrari, and V. Quaresima, "Prefrontal cortex activation during story encoding/retrieval: a multi-channel functional near-infrared spectroscopy study," *Frontiers in Human Neuroscience*, Vol. 7, 2013.

114. van Heuven, W. J., and T. Dijkstra, "Language comprehension in the bilingual brain: fMRI and ERP support for psycholinguistic models," *Brain Research Reviews*, Vol. 64, no. 1, pp. 104–122, 2010.

115. Weber, A., and A. Cutler, "Lexical competition in non-native spoken-word recognition," *Journal of Memory and Language*, Vol. 50, no. 1, pp. 1–25, 2004.

116. Gilbert, S. J., S. Spengler, J. S. Simons, J. D. Steele, S. M. Lawrie, C. D. Frith, and P. W. Burgess, "Functional specialization within rostral prefrontal cortex (area 10): A meta-analysis," *Journal of Cognitive Neuroscience*, Vol. 18, no. 6, pp. 932–948, 2006.

117. Vanderhasselt, M.-A., R. D. Raedt, and C. Baeken, "Dorsolateral prefrontal cortex and stroop performance: Tackling the lateralization," *Psychonomic Bulletin & Review*, Vol. 16, no. 3, pp. 609–612, 2009.

118. Hsu, W.-Y., T. P. Zanto, J. A. Anguera, Y.-Y. Lin, and A. Gazzaley, "Delayed enhancement of multitasking performance: Effects of anodal transcranial direct current stimulation on the prefrontal cortex," *Cortex*, Vol. 69, pp. 175–185, 2015.

119. Verghese, A., K. Garner, J. B. Mattingley, and P. E. Dux, "Prefrontal cortex structure predicts training-induced improvements in multitasking performance," *The Journal of Neuroscience*, Vol. 36, no. 9, pp. 2638–2645, 2016.

120. Gainotti, G., "The role of the right hemisphere in emotional and behavioral disorders of patients with frontotemporal lobar degeneration: An updated review," *Frontiers in Aging Neuroscience*, Vol. 11, 2019.

121. Alves, N. T., S. S. Fukusima, and A. Aznar-Casanova, "Models of brain asymmetry in emotional processing," *Psychology and Neuroscience*, Vol. 1, no. 1, pp. 63–66, 2008.

122. Alexander, J. E., B. Porjesz, L. O. Bauer, S. Kuperman, S. Morzorati, S. J. OConnor, J. Rohrbaugh, H. Begleiter, and J. Polich, "P300 hemispheric amplitude asymmetries from a visual oddball task," *Psychophysiology*, Vol. 32, no. 5, pp. 467–475, 1995.

123. Corballis, P. M., "Visuospatial processing and the right-hemisphere interpreter," *Brain and Cognition*, Vol. 53, no. 2, pp. 171–176, 2003.

124. Grand, R. L., C. J. Mondloch, D. Maurer, and H. P. Brent, "Erratum: Expert face processing requires visual input to the right hemisphere during infancy," *Nature Neuroscience*, Vol. 6, no. 12, pp. 1329–1329, 2003.

125. Pisella, L., N. Alahyane, A. Blangero, F. Thery, S. Blanc, and D. Pelisson, "Right-hemispheric dominance for visual remapping in humans," *Philosophical Transactions of the Royal Society B: Biological Sciences*, Vol. 366, no. 1564, pp. 572–585, 2011.

126. Harrison, M. T., and L. Strother, "Does right hemisphere superiority sufficiently explain the left visual field advantage in face recognition?," *Attention, Perception, & Psychophysics*, Vol. 82, no. 3, pp. 1205–1220, 2019.

127. Ratcliff, G., "Spatial thought, mental rotation and the right cerebral hemisphere," *Neuropsychologia*, Vol. 17, no. 1, pp. 49–54, 1979.

128. Papanicolaou, A. C., G. Deutsch, W. Bourbon, K. W. Will, D. W. Loring, and H. M. Eisenberg, "Convergent evoked potential and cerebral blood flow evidence of task-specific hemispheric differences," *Electroencephalography and Clinical Neurophysiology*, Vol. 66, no. 6, pp. 515–520, 1987.

129. Deutsch, G., W. Bourbon, A. C. Papanicolaou, and H. M. Eisenberg, "Visuospatial tasks compared via activation of regional cerebral blood flow," *Neuropsychologia*, Vol. 26, no. 3, pp. 445–452, 1988.

130. Mutlu, M. C., S. B. Erdoğan, O. C. Öztürk, R. Canbeyli, and H. Saybaşılı, "Functional near-infrared spectroscopy indicates that asymmetric right hemispheric activation in mental rotation of a jigsaw puzzle decreases with task difficulty," *Frontiers in Human Neuroscience*, Vol. 14, 2020.

131. Willems, R. M., M. V. Peelen, and P. Hagoort, "Cerebral lateralization of face-selective and body-selective visual areas depends on handedness," *Cerebral Cortex*, Vol. 20, no. 7, pp. 1719–1725, 2009.

132. Zhen, Z., Z. Yang, L. Huang, X. zhen Kong, X. Wang, X. Dang, Y. Huang, Y. Song, and J. Liu, "Quantifying interindividual variability and asymmetry of face-selective regions: A probabilistic functional atlas," *NeuroImage*, Vol. 113, pp. 13–25, 2015.

133. Stephan, K. E., "Lateralized cognitive processes and lateralized task control in the human brain," *Science*, Vol. 301, no. 5631, pp. 384–386, 2003.

134. Linden, D. E., D. Prvulovic, E. Formisano, M. Völlinger, F. E. Zanella, R. Goebel, and T. Dierks, "The functional neuroanatomy of target detection: An fMRI study of visual and auditory oddball tasks," *Cerebral Cortex*, Vol. 9, no. 8, pp. 815–823, 1999.

135. Rizer, W., J. S. Aday, and J. M. Carlson, "Changes in prefrontal cortex near infrared spectroscopy activity as a function of difficulty in a visual p300 paradigm," *Journal of Near Infrared Spectroscopy*, Vol. 26, no. 4, pp. 222–228, 2018.

136. Ardekani, B. A., S. J. Choi, G.-A. Hossein-Zadeh, B. Porjesz, J. L. Tanabe, K. O. Lim, R. Bilder, J. A. Helpern, and H. Begleiter, "Functional magnetic resonance imaging of brain activity in the visual oddball task," *Cognitive Brain Research*, Vol. 14, no. 3, pp. 347–356, 2002.

137. Proulx, N., A.-A. Samadani, and T. Chau, "Quantifying fast optical signal and event-related potential relationships during a visual oddball task," *NeuroImage*, Vol. 178, pp. 119–128, 2018.

138. Clark, V. P., S. Fannon, S. Lai, R. Benson, and L. Bauer, "Responses to rare visual target and distractor stimuli using event-related fMRI," *Journal of Neurophysiology*, Vol. 83, no. 5, pp. 3133–3139, 2000.

139. Stevens, A. A., P. Skudlarski, J. Gatenby, and J. C. Gore, "Event-related fMRI of auditory and visual oddball tasks," *Magnetic Resonance Imaging*, Vol. 18, no. 5, pp. 495–502, 2000.

140. Kiehl, K. A., and P. F. Liddle, "An event-related functional magnetic resonance imaging study of an auditory oddball task in schizophrenia," *Schizophrenia Research*, Vol. 48, no. 2-3, pp. 159–171, 2001.

141. Kirino, E., A. Belger, P. Goldman-Rakic, and G. McCarthy, "Prefrontal activation evoked by infrequent target and novel stimuli in a visual target detection task: An event-related functional magnetic resonance imaging study," *The Journal of Neuroscience*, Vol. 20, no. 17, pp. 6612–6618, 2000.

142. Peirce, J., J. R. Gray, S. Simpson, M. MacAskill, R. Höchenberger, H. Sogo, E. Kastman, and J. K. Lindeløv, "PsychoPy2: Experiments in behavior made easy," *Behavior Research Methods*, Vol. 51, no. 1, pp. 195–203, 2019.

143. Jang, K. E., S. Tak, J. Jung, J. Jang, Y. Jeong, and J. C. Ye, "Wavelet minimum description length detrending for near-infrared spectroscopy," *Journal of Biomedical Optics*, Vol. 14, no. 3, p. 034004, 2009.

144. Singh, A. K., M. Okamoto, H. Dan, V. Jurcak, and I. Dan, "Spatial registration of multichannel multi-subject fNIRS data to MNI space without MRI," *NeuroImage*, Vol. 27, no. 4, pp. 842–851, 2005.

145. Ye, J., S. Tak, K. Jang, J. Jung, and J. Jang, "NIRS-SPM: Statistical parametric mapping for near-infrared spectroscopy," *NeuroImage*, Vol. 44, no. 2, pp. 428–447, 2009.

146. Shepard, R. N., and J. Metzler, “Mental rotation of three-dimensional objects,” *Science*, Vol. 171, no. 3972, pp. 701–703, 1971.

147. Jordan, K., H.-J. Heinze, K. Lutz, M. Kanowski, and L. JÃncke, “Cortical activations during the mental rotation of different visual objects,” *NeuroImage*, Vol. 13, no. 1, pp. 143–152, 2001.

148. Halari, R., T. Sharma, M. Hines, C. Andrew, A. Simmons, and V. Kumari, “Comparable fMRI activity with differential behavioural performance on mental rotation and overt verbal fluency tasks in healthy men and women,” *Experimental Brain Research*, Vol. 169, no. 1, pp. 1–14, 2005.

149. Shimoda, N., K. Takeda, I. Imai, J. Kaneko, and H. Kato, “Cerebral laterality differences in handedness: A mental rotation study with NIRS,” *Neuroscience Letters*, Vol. 430, no. 1, pp. 43–47, 2008.

150. Harris, I. M., G. F. Egan, C. Sonkkila, H. J. Tochon-Danguy, G. Paxinos, and J. D. G. Watson, “Selective right parietal lobe activation during mental rotation,” *Brain*, Vol. 123, no. 1, pp. 65–73, 2000.

151. Cooper, L. A., and R. N. Shepard, “Mental transformation in the identification of left and right hands.,” *Journal of Experimental Psychology: Human Perception and Performance*, Vol. 1, no. 1, pp. 48–56, 1975.

152. Hugdahl, K., T. Thomsen, and L. Ersland, “Sex differences in visuo-spatial processing: An fMRI study of mental rotation,” *Neuropsychologia*, Vol. 44, no. 9, pp. 1575–1583, 2006.

153. Suchan, B., L. YágÃ¼ez, G. Wunderlich, A. G. Canavan, H. Herzog, L. Tellmann, V. HÃ¶mberg, and R. J. Seitz, “Hemispheric dissociation of visual-pattern processing and visual rotation,” Vol. 136, pp. 533–544, nov 2002.

154. Mehta, Z., and F. Newcombe, “A role for the left hemisphere in spatial processing,” *Cortex*, Vol. 27, no. 2, pp. 153–167, 1991.

155. Alivisatos, B., and M. Petrides, “Functional activation of the human brain during mental rotation,” *Neuropsychologia*, Vol. 35, no. 2, pp. 111–118, 1997.

156. Cohen, M. S., S. M. Kosslyn, H. C. Breiter, G. J. DiGirolamo, W. L. Thompson, A. K. Anderson, S. Y. Bookheimer, B. R. Rosen, and J. W. Belliveau, “Changes in cortical activity during mental rotation a mapping study using functional MRI,” *Brain*, Vol. 119, no. 1, pp. 89–100, 1996.

157. Vingerhoets, G., F. P. de Lange, P. Vandemaele, K. Deblaere, and E. Achten, “Motor imagery in mental rotation: An fMRI study,” *NeuroImage*, Vol. 17, no. 3, pp. 1623–1633, 2002.

158. Ditunno, P. L., and V. A. Mann, “Right hemisphere specialization for mental rotation in normals and brain damaged subjects,” *Cortex*, Vol. 26, no. 2, pp. 177–188, 1990.

159. Corballis, M. C., “Mental rotation and the right hemisphere,” *Brain and Language*, Vol. 57, no. 1, pp. 100–121, 1997.

160. Yanagisawa, H., I. Dan, D. Tsuzuki, M. Kato, M. Okamoto, Y. Kyutoku, and H. Soya, “Acute moderate exercise elicits increased dorsolateral prefrontal activation and improves cognitive performance with stroop test,” *NeuroImage*, Vol. 50, no. 4, pp. 1702–1710, 2010.

161. Kujach, S., K. Byun, K. Hyodo, K. Suwabe, T. Fukuie, R. Laskowski, I. Dan, and H. Soya, "A transferable high-intensity intermittent exercise improves executive performance in association with dorsolateral prefrontal activation in young adults," *NeuroImage*, Vol. 169, pp. 117–125, 2018.

162. Leung, H.-C., J. C. Gore, and P. S. Goldman-Rakic, "Sustained mnemonic response in the human middle frontal gyrus during on-line storage of spatial memoranda," *Journal of Cognitive Neuroscience*, Vol. 14, no. 4, pp. 659–671, 2002.

163. Slotnick, S. D., and L. R. Moo, "Prefrontal cortex hemispheric specialization for categorical and coordinate visual spatial memory," *Neuropsychologia*, Vol. 44, no. 9, pp. 1560–1568, 2006.

164. Daniel, T. A., J. S. Katz, and J. L. Robinson, "Delayed match-to-sample in working memory: A BrainMap meta-analysis," *Biological Psychology*, Vol. 120, pp. 10–20, 2016.

165. Christie, J., J. P. Ginsberg, J. Steedman, J. Fridriksson, L. Bonilha, and C. Rorden, "Global versus local processing: seeing the left side of the forest and the right side of the trees," *Frontiers in Human Neuroscience*, Vol. 6, 2012.

166. Brederoo, S. G., M. R. Nieuwenstein, M. M. Lorist, and F. W. Cornelissen, "Hemispheric specialization for global and local processing: A direct comparison of linguistic and non-linguistic stimuli," *Brain and Cognition*, Vol. 119, pp. 10–16, 2017.

167. Hugdahl, K., K. Brønnick, S. Kyllingsbrk, I. Law, A. Gade, and O. B. Paulson, "Brain activation during dichotic presentations of consonant-vowel and musical instrument stimuli: a 15 o-PET study," *Neuropsychologia*, Vol. 37, no. 4, pp. 431–440, 1999.

168. Abrahams, S., L. H. Goldstein, A. Simmons, M. J. Brammer, S. C. Williams, V. P. Giampietro, C. M. Andrew, and P. N. Leigh, "Functional magnetic resonance imaging of verbal fluency and confrontation naming using compressed image acquisition to permit overt responses," *Human Brain Mapping*, Vol. 20, no. 1, pp. 29–40, 2003.

169. Wildgruber, D., A. Riecker, I. Hertrich, M. Erb, W. Grodd, T. Ethofer, and H. Ackermann, "Identification of emotional intonation evaluated by fMRI," *NeuroImage*, Vol. 24, no. 4, pp. 1233–1241, 2005.

170. Mitchell, R. L. C., "Right hemisphere language functions and schizophrenia: the forgotten hemisphere?," *Brain*, Vol. 128, no. 5, pp. 963–978, 2005.

171. Lindell, A. K., "In your right mind: Right hemisphere contributions to language processing and production," *Neuropsychology Review*, Vol. 16, no. 3, pp. 131–148, 2006.

172. Neville, H., J. L. Nicol, A. Barss, K. I. Forster, and M. F. Garrett, "Syntactically based sentence processing classes: Evidence from event-related brain potentials," *Journal of Cognitive Neuroscience*, Vol. 3, no. 2, pp. 151–165, 1991.

173. Caplan, D., N. Alpert, G. Waters, and A. Olivieri, "Activation of brocas area by syntactic processing under conditions of concurrent articulation," *Human Brain Mapping*, Vol. 9, no. 2, pp. 65–71, 2000.

174. Wilson, S. M., S. Galantucci, M. C. Tartaglia, and M. L. Gorno-Tempini, "The neural basis of syntactic deficits in primary progressive aphasia," *Brain and Language*, Vol. 122, no. 3, pp. 190–198, 2012.

175. Zaccarella, E., M. Schell, and A. D. Friederici, "Reviewing the functional basis of the syntactic merge mechanism for language: A coordinate-based activation likelihood estimation meta-analysis," *Neuroscience & Biobehavioral Reviews*, Vol. 80, pp. 646–656, 2017.

176. Peristeri, E., I. M. Tsimpli, E. Dardiotis, and K. Tsapkini, "Effects of executive attention on sentence processing in aphasia," *Aphasiology*, Vol. 34, no. 8, pp. 943–969, 2019.

177. Dempsey, J., Q. Liu, and K. Christianson, "Convergent probabilistic cues do not trigger syntactic adaptation: Evidence from self-paced reading.," *Journal of Experimental Psychology: Learning, Memory, and Cognition*, Vol. 46, no. 10, pp. 1906–1921, 2020.

178. Santi, A., and Y. Grodzinsky, "fMRI adaptation dissociates syntactic complexity dimensions," *NeuroImage*, Vol. 51, no. 4, pp. 1285–1293, 2010.

179. Sambin, S., M. Teichmann, R. de Diego Balaguer, M. Giavazzi, D. Sportiche, P. Schlenker, and A.-C. Bachoud-Lévi, "The role of the striatum in sentence processing: Disentangling syntax from working memory in huntington's disease," *Neuropsychologia*, Vol. 50, no. 11, pp. 2625–2635, 2012.

180. Özge, D., T. Marinis, and D. Zeyrek, "Comprehension of subject and object relative clauses in monolingual turkish children," in *In J. Chandlee, K. Franich, K. Iserman, L. Keil (Eds.), Proceedings Supplement to the 34th Boston University Conference on Language Development (BUCLD, 34)*, 2009.

181. Bulut, T., S.-K. Cheng, K.-Y. Xu, D. L. Hung, and D. H. Wu, "Is there a processing preference for object relative clauses in chinese? evidence from ERPs," *Frontiers in Psychology*, Vol. 9, 2018.

182. Carreiras, M., J. A. Duñabeitia, M. Vergara, I. de la Cruz-Pavía, and I. Laka, "Subject relative clauses are not universally easier to process: Evidence from basque," *Cognition*, Vol. 115, no. 1, pp. 79–92, 2010.

183. Sung, Y.-T., J.-Y. Tu, J.-H. Cha, and M.-D. Wu, "Processing preference toward object-extracted relative clauses in mandarin chinese by l1 and l2 speakers: An eye-tracking study," *Frontiers in Psychology*, Vol. 7, 2016.

184. Traxler, M. J., R. K. Morris, and R. E. Seely, "Processing subject and object relative clauses: Evidence from eye movements," *Journal of Memory and Language*, Vol. 47, no. 1, pp. 69–90, 2002.

185. Ding, G., K. A. J. Mohr, C. I. Orellana, A. S. Hancock, S. Juth, R. Wada, and R. B. Gillam, "Use of functional near infrared spectroscopy to assess syntactic processing by monolingual and bilingual adults and children," *Frontiers in Human Neuroscience*, Vol. 15, 2021.

186. Mak, W. M., W. Vonk, and H. Schriefers, "The influence of animacy on relative clause processing," *Journal of Memory and Language*, Vol. 47, no. 1, pp. 50–68, 2002.

187. King, J. W., and M. Kutas, "Who did what and when? using word- and clause-level ERPs to monitor working memory usage in reading," *Journal of Cognitive Neuroscience*, Vol. 7, no. 3, pp. 376–395, 1995.

188. Schriefers, H., A. Friederici, and K. Kuhn, "The processing of locally ambiguous relative clauses in german," *Journal of Memory and Language*, Vol. 34, no. 4, pp. 499–520, 1995.

189. Hsiao, Y., and M. C. MacDonald, "Experience and generalization in a connectionist model of mandarin chinese relative clause processing," *Frontiers in Psychology*, Vol. 4, 2013.

190. Özge, D., T. Marinis, and D. Zeyrek, "Incremental processing in head-final child language: online comprehension of relative clauses in turkish-speaking children and adults," *Language, Cognition and Neuroscience*, Vol. 30, no. 9, pp. 1230–1243, 2015.

191. Özge, D., *Mechanisms and Strategies in the Processing and Acquisition of Relative Clauses in Turkish Monolingual and Turikish-English Bilingual Children.* PhD thesis, Middle East Technical University, Ankara, Turkey, 2010.

192. Kahraman, B., A. Sato, H. Ono, and H. Sakai, "Relative clauses processing before the headnoun: Evidence for strong forward prediction in turkish," in *Proceedings of the 6th Workshop on Altaic Formal Linguistics (WAFL6). MIT Working Papers in Linguistics 61*, pp. 155–170, MIT Press, 2010.

193. Kahraman, B., "Processing turkish relative clauses in context," in *Ankara Papers in Turkish and Turkic Linguistics*, pp. 98–109, Harrassowitz, O, 2015.

194. Uzundağ, B. A., and A. C. Küntay, "The acquisition and use of relative clauses in turkish-learning children's conversational interactions: a cross-linguistic approach," *Journal of Child Language*, Vol. 46, no. 6, pp. 1142–1168, 2019.

195. Başer, Z., and A. Hohenberger, "Is there a particular RC attachment preference in turkish? negotiating the effects of semantic factors," *Journal of Psycholinguistic Research*, Vol. 49, no. 4, pp. 511–539, 2020.

196. Kovelman, I., S. A. Baker, and L.-A. Petitto, "Bilingual and monolingual brains compared: A functional magnetic resonance imaging investigation of syntactic processing and a possible "neural signature" of bilingualism," *Journal of Cognitive Neuroscience*, Vol. 20, no. 1, pp. 153–169, 2008.

197. Hassanpour, M. S., A. T. Eggebrecht, J. P. Culver, and J. E. Peelle, "Mapping cortical responses to speech using high-density diffuse optical tomography," *NeuroImage*, Vol. 117, pp. 319–326, 2015.

198. Rogers, R. D., A. M. Owen, H. C. Middleton, E. J. Williams, J. D. Pickard, B. J. Sahakian, and T. W. Robbins, "Choosing between small, likely rewards and large, unlikely rewards activates inferior and orbital prefrontal cortex," *The Journal of Neuroscience*, Vol. 19, no. 20, pp. 9029–9038, 1999.

199. Ernst, M., E. E. Nelson, E. B. McClure, C. S. Monk, S. Munson, N. Eshel, E. Zarahn, E. Leibenluft, A. Zametkin, K. Towbin, J. Blair, D. Charney, and D. S. Pine, "Choice selection and reward anticipation: an fMRI study," *Neuropsychologia*, Vol. 42, no. 12, pp. 1585–1597, 2004.

200. Hugdahl, K., A. Lundervold, L. Ersland, A. I. Smievoll, H. Sundbekg, R. Bakndon, and B. E. Roscher, "Left frontal activation during a semantic categorization task: An fMRI-study," *International Journal of Neuroscience*, Vol. 99, no. 1-4, pp. 49–58, 1999.

201. Wang, S., Z. Zhu, J. X. Zhang, Z. Wang, Z. Xiao, H. Xiang, and H.-C. Chen, "Brocas area plays a role in syntactic processing during chinese reading comprehension," *Neuropsychologia*, Vol. 46, no. 5, pp. 1371–1378, 2008.

202. F, N. A., "Cognitive load theory in the context of second language academic writing," *Higher Education Pedagogies*, Vol. 3, no. 1, pp. 385–402, 2018.

203. Park, H., J.-S. Kang, S. Choi, and M. Lee, "Analysis of cognitive load for language processing based on brain activities," in *Neural Information Processing*, pp. 561–568, Springer Berlin Heidelberg, 2013.

204. Christodoulides, G., *Effects of Cognitive Load on Speech Production and Perception*. PhD thesis, UniversitÃ© catholique de Louvain, Louvain , Belgium, 2016.

205. Dans, P. W., S. D. Foglia, and A. J. Nelson, "Data processing in functional near-infrared spectroscopy (fNIRS) motor control research," *Brain Sciences*, Vol. 11, no. 5, p. 606, 2021.

206. Pinti, P., F. Scholkmann, A. Hamilton, P. Burgess, and I. Tachtsidis, "Current status and issues regarding pre-processing of fNIRS neuroimaging data: An investigation of diverse signal filtering methods within a general linear model framework," *Frontiers in Human Neuroscience*, Vol. 12, 2019.

207. Webster, J. G., ed., *Medical Instrumentation: Application and Design*, NJ, USA: John Wiley Sons, 4th ed., 2010.

208. KV, S., and K. D. Smet, "Sensor data fusion framework for improvement of temperature sensor characteristics," *Measurement and Control*, Vol. 49, no. 7, pp. 219–229, 2016.

209. Assumpcao, D., S. Kumar, V. Narasimhan, J. Lee, and H. Choo, "High-performance flexible metal-on-silicon thermocouple," *Scientific Reports*, Vol. 8, no. 1, 2018.

210. Yu, W. L., Z. Wang, and L. Jin, "The experiment study on infrared radiation spectrum of human body," in *Proceedings of 2012 IEEE-EMBS International Conference on Biomedical and Health Informatics*, IEEE, 2012.

211. Aasted, C. M., M. A. YÃ¼cel, R. J. Cooper, J. Dubb, D. Tsuzuki, L. Becerra, M. P. Petkov, D. Borsook, I. Dan, and D. A. Boas, "Anatomical guidance for functional near-infrared spectroscopy: AtlasViewer tutorial," *Neurophotonics*, Vol. 2, no. 2, p. 020801, 2015.

212. Benavides-Varela, S., R. Siugzdaite, D. M. Gómez, F. Macagno, L. Cattarossi, and J. Mehler, "Brain regions and functional interactions supporting early word recognition in the face of input variability," *Proceedings of the National Academy of Sciences*, Vol. 114, no. 29, pp. 7588–7593, 2017.

213. Caplan, D., S. Vijayan, G. Kuperberg, C. West, G. Waters, D. Greve, and A. M. Dale, "Vascular responses to syntactic processing: Event-related fMRI study of relative clauses," *Human Brain Mapping*, Vol. 15, no. 1, pp. 26–38, 2001.

214. Carbonell, F., P. Bellec, and A. Shmuel, "Global and system-specific resting-state fMRI fluctuations are uncorrelated: Principal component analysis reveals anti-correlated networks," *Brain Connectivity*, Vol. 1, no. 6, pp. 496–510, 2011.

215. DEsposito, M., B. Postle, D. Ballard, and J. Lease, "Maintenance versus manipulation of information held in working memory: An event-related fMRI study," *Brain and Cognition*, Vol. 41, no. 1, pp. 66–86, 1999.

216. Erdoğan, S. B., Y. Tong, L. M. Hocke, K. P. Lindsey, and B. deB Frederick, "Correcting for blood arrival time in global mean regression enhances functional connectivity analysis of resting state fMRI-BOLD signals," *Frontiers in Human Neuroscience*, Vol. 10, 2016.

217. Hervé, P.-Y., L. Zago, L. Petit, B. Mazoyer, and N. Tzourio-Mazoyer, "Revisiting human hemispheric specialization with neuroimaging," *Trends in Cognitive Sciences*, Vol. 17, no. 2, pp. 69–80, 2013.

218. Kohno, S., I. Miyai, A. Seiyama, I. Oda, A. Ishikawa, S. Tsuneishi, T. Amita, and K. Shimizu, "Removal of the skin blood flow artifact in functional near-infrared spectroscopic imaging data through independent component analysis," *Journal of Biomedical Optics*, Vol. 12, no. 6, p. 062111, 2007.

219. MacDonald, M. C., and M. H. Christiansen, "Reassessing working memory: Comment on just and carpenter (1992) and waters and caplan (1996).," *Psychological Review*, Vol. 109, no. 1, pp. 35–54, 2002.

220. Ng, V. W., P. J. Eslinger, S. C. Williams, M. J. Brammer, E. T. Bullmore, C. M. Andrew, J. Suckling, R. G. Morris, and A. L. Benton, "Hemispheric preference in visuospatial processing: A complementary approach with fMRI and lesion studies," *Human Brain Mapping*, Vol. 10, no. 2, pp. 80–86, 2000.

221. Nowak, M. A., and D. C. Krakauer, "The evolution of language," *Proceedings of the National Academy of Sciences*, Vol. 96, no. 14, pp. 8028–8033, 1999.

222. Rorden, C., and M. Brett, "Stereotaxic display of brain lesions," *Behavioural Neurology*, Vol. 12, no. 4, pp. 191–200, 2000.

223. Saager, R. B., N. L. Telleri, and A. J. Berger, "Two-detector corrected near infrared spectroscopy (c-NIRS) detects hemodynamic activation responses more robustly than single-detector NIRS," *NeuroImage*, Vol. 55, no. 4, pp. 1679–1685, 2011.

224. Santosa, H., M. J. Hong, S.-P. Kim, and K.-S. Hong, "Noise reduction in functional near-infrared spectroscopy signals by independent component analysis," *Review of Scientific Instruments*, Vol. 84, no. 7, p. 073106, 2013.

225. Seepanomwan, K., D. Caligiore, A. Cangelosi, and G. Baldassarre, "Generalisation, decision making, and embodiment effects in mental rotation: A neurorobotic architecture tested with a humanoid robot," *Neural Networks*, Vol. 72, pp. 31–47, 2015.

226. Seydell-Greenwald, A., K. Ferrara, C. E. Chambers, E. L. Newport, and B. Landau, "Bilateral parietal activations for complex visual-spatial functions: Evidence from a visual-spatial construction task," *Neuropsychologia*, Vol. 106, pp. 194–206, 2017.

227. Webster, J. G., "Medical instrumentation-application and design," *Journal of Clinical Engineering*, Vol. 3, no. 3, p. 306, 1978.

228. Xu, K., J.-R. Duann, D. L. Hung, and D. H. Wu, "Preference for object relative clauses in chinese sentence comprehension: Evidence from online self-paced reading time," *Frontiers in Psychology*, Vol. 10, 2019.

229. Zhang, Y., D. H. Brooks, M. A. Franceschini, and D. A. Boas, "Eigenvector-based spatial filtering for reduction of physiological interference in diffuse optical imaging," *Journal of Biomedical Optics*, Vol. 10, no. 1, p. 011014, 2005.