

T.C.

YEDİTEPE UNIVERSITY

INSTITUTE OF HEALTH SCIENCES

NEUROSCIENCE PROGRAM

**EVALUATION OF HUMAN AND ROBOT FACES
AND VOICES THROUGH BEHAVIOURAL AND
NEUROIMAGING METHODS**

DOCTOR OF PHILOSOPHY THESIS

EMRE YORGANCIGİL, PhD

İSTANBUL-2021

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This thesis has been deemed by the jury in accordance with the relevant articles of Yeditepe University Graduate Education and Examinations Regulation and has been approved by Administrative Board of Institute with decision dated 31.12.2021 and numbered 2021/13-02.

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DECLARATION

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree except where due acknowledgment has been made in the text.

29.12.2021

Emre YORGANCIGIL



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LIST OF SYMBOLS AND ABBREVIATIONS

ANOVA	Analysis of Variance
BA	Brodman Area
C11	Component 11
cm	Centimeter
CW	Continuous wave
deoxy-Hb	dexoygeneated hemoglobin
DLPFC	Dorsolateral Prefrontal Cortex
dmPFC	Dorsomedial Prefrontal Cortex
EEG	Electro Encephalography
ERP	Event Related Potentials
F	F test
FFA	Fusiform Face Area
fMRI	Functional Magnetic Resonance Imaging
fNIRS	Functional Near Infrared Spectroscopy
HRI	Human-Robot Interactions
Hz	Heartz
İYKAS	İşlevsel Yakın Kızıl Altı Spektroskopisi
IOFC	Lateral Orbito Frontal Cortex
LC	Locus Coeruleus
LCD	Liquid Crystal Display
LPFC	Lateral Prefrontal Cortex
M	Mean
MEG	Magneto Encephalography

MNI	Montreal Neurological Institute
mm ²	Square Milimeter
ms	Milisecond
n	Number
N170	Negative 170
nm	Nanometer
OD	Optical Density
OFC	Orbito Frontal Cortex
oxy-Hb	Oxygeneated Hemoglobin
p	Probability value
P1	Positive 100
PET	Position Emitting Topography
PFC	Prefrontal Cortex
S.E.	Standart Error
SD	Standart Deviation
STS	Superior Temporal Sulcus
t	T-Statistic
USA	United States of America
vmPFC	Ventromedial Prefrontal Cortex
VPP	Vertex Positive Potential
VTA	Vental Tegmental Area
®	Registered Trademark
η^2p	Partial Eta Squared
Δ	Delta

ABSTRACT

Yorgancıgil, E. (2021). Evaluation of Human and Robot Faces and Voices through Behavioural and Neuroimaging Methods, Yeditepe University, Institute of Health Science, Department of Neuroscience, PhD thesis, İstanbul.

Human-robot interactions have become important with the widespread use of robots in our daily lives. As we encounter robots from the simplest designs to humanoid designs, communication with robots becomes linearly easier. However, humanoid robot designs break this linear line and people may feel sudden revulsion and uncanny feelings towards these designs. This effect is called the uncanny valley effect. In our study; we investigated how the uncanny valley effect occurs, how voices and faces of robot and human designs are perceived by using behavioural and neuroimaging methods. 60 participants, 30 younger and 30 older, participated in the behavioural experiment. Unrealistic, semi-realistic and realistic voice and face designs were rated by the participants according to their feelings of normality and uncanniness. 35 healthy adults participated in the neuroimaging experiments, which is the second part of the thesis. Prefrontal cortex activities were recorded using fNIRS (functional near infrared spectroscopy) while the participants watched videos containing human and robot faces and voices. According to the results of the behavioural experiment step; multimodal auditory and visual stimuli elicited more uncanny feelings in participants than the unimodal auditory-only and visual-only stimuli. We indicated that the older participants showed more linear response from less realistic to realistic, but the younger participants showed a more sensitive response to different sound and image levels. In the results of the neuroimaging experiment; left lateral and partially right lateral areas of the prefrontal cortex were found to have a specific response to changes in robot and human voice and face stimuli. As a result of our study, it was determined that human and robot interactions are processed cognitively and physiologically in the human brain and create specific responses depending on different auditory and visual aspects. We also suggest that the uncanny valley effect has a physiological effect in the brain in addition to its cognitive effect. This exploratory study shows that human-robot interactions should be studied in a multidimensional manner with cognitive and neuroscientific methods.

Keywords: Human-robot interactions, uncanny valley effect, face and voice design, prefrontal cortex, fNIRS measurement

ÖZET

Yorgancıgil, E. (2021). İnsan ve Robot Yüz ve Seslerinin Davranışsal ve Nörogörüntüleme Yöntemleriyle İncelenmesi, Yeditepe Üniversitesi Sağlık Bilimleri Enstitüsü, Sinirbilim ABD., Doktora Tezi, İstanbul.

Robotların günlük hayatımızda yaygınlaşmasıyla birlikte insan-robot etkileşimleri önem kazanmıştır. En basit robot tasarımlarından insansı robotlara kadar, robotlarla iletişim doğrusal olarak kolaylaşmaktadır. Ancak insansı robot tasarımları bu doğrusal çizgiyi kırar ve bir anda insanlar bu tasarımlara karşı tiksinti ve esrarengiz duygular hissederler. Bu etkiye “tekinsiz vadi etkisi” denir. Çalışmamızda; tekinsiz vadi etkisinin nasıl oluştuğunu, robot ve insan tasarımlarının seslerinin ve yüzlerinin nasıl algılandığını davranışsal ve nörogörüntüleme yöntemleriyle araştırdık. Davranışsal deneylere 30'u genç, 30'u yaşlı olmak üzere 60 katılımcı ile gerçekleştirildi. Gerçekçi olmayan, yarı gerçekçi ve gerçekçi ses ve yüz tasarımları, katılımcılar tarafından normallik ve tekinsizlik duygularına göre derecelendirildi. Çalışmanın diğer aşaması olan beyin görüntüleme deneylerine 35 sağlıklı yetişkin katıldı. Prefrontal korteks aktiviteleri İYKAS (işlevsel yakın kızılaltı spektroskopisi) yöntemi ile kaydedilirken, katılımcılar insan ve robot yüzleri ve seslerini içeren videolar izlediler. Davranışsal deney aşamasının sonuçlarına göre; çok modlu işitsel ve görsel uyaranlar, katılımcılarda tek modlu yalnızca işitsel ve yalnızca görsel uyaranlardan daha fazla tekinsiz duygular uyandırdı. Daha yaşlı katılımcıların daha az gerçekçiden gerçekçiye doğru daha doğrusal tepki verdiğini, ancak genç katılımcıların farklı ses ve görüntü seviyelerine daha hassas tepki verdiğini gözlemledik. Nörogörüntüleme deneyinin sonuçlarına göre; prefrontal korteksin sol lateral ve kısmen sağ lateral bölgelerinin robot ve insan sesindeki ve yüz uyaranlarındaki değişikliklere spesifik bir tepki verdiği bulundu. Çalışmamız sonucunda insan ve robot etkileşimlerinin insan beyninde bilişsel ve fizyolojik olarak işlendiği ve farklı işitsel ve görsel düzeylere bağlı olarak belirli tepkiler oluşturduğu belirlenmiştir. Tekinsiz vadi etkisinin, bilişsel etkiye ek olarak beyin üzerinde fizyolojik bir etkisi olduğunu da varsaydık. Bu keşifsel çalışma, insan-robot etkileşimlerinin bilişsel ve sinirbilim yöntemleriyle çok boyutlu olarak incelenmesi gerektiğini göstermektedir.

Anahtar Kelimeler: İnsan-robot etkileşimleri, tekinsiz vadi etkisi, yüz ve ses tasarımları, prefrontal korteks, İYKAS ölçümü

1.INTRODUCTION and PURPOSE

In our study, we use two experimental research methods to evaluate the emotional reactions towards human and robot faces. In the behavioural experiment, we explore the effect of different sensory modalities, naturalness levels and age effect on the cognition of human and robot faces. Neuroimaging experiment was set up to find specific human prefrontal cortex activity with using human and robot face stimuli.

Exploring human-robot interactions (HRI) is a relatively new research topic, yet gaining importance as more types of robots are becoming part of our daily lives. From entertainment to manufacturing services, robots are used as advanced tools and give essential assistance to humans. Widespread use of robots in daily life results in more common and complex contact patterns between humans and robots, which have physical and psychological aspects. Physical interactions between humans and robots are multifaceted and multi-layered and involve highly productive emotional and behavioural perceptions and processes. HRI research primarily aims to find convenient behavioural patterns between robots and humans, beneficial roles of robots to humans and proper robot design to be easily accepted by humans ¹. As robots become ordinary elements of the human environment, their cognitive impressions started taking roots in the human brain.

Robot designs are one of the core points to how humans interact with robots. Human-like designed robots have to be easily interacted with humans as pre-acceptance, but the uncanny valley phenomenon contradicts this. Uncanny valley hypothesis suggests that human-like and humanoid objects create uncanny feelings in observers when they reach the almost human level. A valley-like curve can describe this relationship, and indicates a sharp dip in this curve at almost human-like levels as an uncanny valley ². According to several anthropological and evolutionary theories about uncanny valley, cognitive dissonance may be a plausible reason for uncanny feelings ³. Face-voice mismatch effect subverts categorical boundaries about robot and human definitions in our perception, as previous studies openly presented ^{4,5}. Perceptual and cognitive effects of robots can be addressed in prefrontal cortex areas in the human brain ⁶.

We have three research questions for the behavioural experiment step. Our first research question is to test visual, auditory and audio-visual components' dominance on uncanny valley phenomenon. In line with previous findings, we investigated whether the

facial features, the robot voice or the combined cues from both modalities (face and voice) are the determining factor in the emergence of uncanny feelings. Second research question is if incongruence between face-voice will result in an amplified uncanny valley effect. We used humanoid and robot designs that may trigger an uncanny valley effect. Since the robot face is a prominent actor of the robot's general appearance in human-robot interactions, we used face stimuli and changed texture to create different human-likeness levels ⁷. Similarly, we changed the frequency of robot voices to create a similar effect. Third research question is if age of the participants is a significant factor in determining the uncanniness perception. We explored how participants categorized by age (young and old), rated our audio-visual stimulus as uncanny to normal feelings.

Depending on this complex perspective of human-robot interactions and its cognitive roots in the human brain; in the neuroimaging experiment step we aimed to explore the differences and similarities between perceptual and emotional processing of human and robot faces by interpreting the hemodynamic correlates of these stimuli. For this purpose, real human face and voice stimuli and custom designed robot face and voice stimuli were presented to participants while their hemodynamic responses were recorded with an fNIRS instrument which had a probe covering the prefrontal cortex. After the experiments, participants rated human and robot stimuli based on the strength of the unpleasant feelings produced. Hemodynamic responses to human and robot stimuli and congruent and incongruent face and voice pairs of human and robot stimuli were investigated with fNIRS method.

1.1. Introduction to Behavioural Experiment

“Uncanny Valley Hypothesis” suggests that almost human-like, but not real human entities may elicit uncanny and eeriness feelings ⁸. While the uncanny valley has been largely investigated with a focus on the visual aspects of the robot-like designs with young adults, the auditory components that may contribute to this effect and how visual and auditory factors jointly play a role in uncanny reports across different generations has not been examined. In the behavioural experiment, we investigated how multimodal stimuli and the congruence of visual and auditory aspects of the stimuli contribute to the uncanniness perception and differ from the auditory and visual components across generations.

1.1.1. Age Factor in Uncanny Valley

Age can be a potent factor for the uncanny valley effect. A body of human-robot interaction studies compare how different generations react to robot designs and robotic behaviours⁹. Children can feel discomfort with human-like robots and uncanny valley effect could emerge with improved mental capacity in older children^{10,11}. Although there has been an increased interest in understanding uncanny valley from a developmental perspective including children, there are much less studies involving older generations¹². A handful of studies show that elderly people have more negative attitudes to assistive technology and devices. For instance, older adults feel warmer emotions to humans than robots and prefer interacting with robots or humanoids only in consistent appearance^{13,14}.

1.1.2. Research Questions and Purpose of the Behavioural Experiment

If the uncanny valley effect is due to the termination of expectancy, people should find matching audio and visuals less uncanny, even if they are perceived more disturbing. On the other hand, if the uncanny valley effect is an outcome depending solely on the level of unnaturalness, then regardless of the congruency between visual and auditory aspects disturbing unimodal sensory stimuli should determine the level of uncanniness.

The aim of the behavioural experiment is to test the individual and joint contribution of visual and auditory modalities on the uncanny reports in two different age groups. To this end, we investigated how the facial features (visual), the voice (auditory) and a combination of the two the uncanny reports. We used computer animations that vary in terms of naturalness in both visual and auditory modalities.

1.2. Introduction to Neuroimaging Experiment

With the rapid advances in robotic technology, automated systems such as social robots, and virtual agents have taken an increasing number of roles to facilitate our daily lives. One critical question to be addressed is whether human-human and human-robot interactions share the same neuropsychological and neurophysiological mechanisms and if so, how this information could be used to calibrate human reactions during human-robot interactions will improve our experience with robots. Human-robot interactions consist of complex cognitive mechanisms which can be summarized as social cognition and emotional regulation²⁰⁹.

fNIRS (Functional Near Infrared Spectroscopy) is a neuro-imaging method which is based on cerebral hemodynamic responses. fNIRS can be a preferred method for PFC

studies in many aspects: To search anatomical locations of emotional responses in PFC and sublocations of PFC, to study neural mechanisms in emotion-action interaction process and mood-cognition experiments and emotional executive functions are all studied with fNIRS method ¹⁸⁴. Natural environment friendly settings of fNIRS methodology are an advance to evaluate neural mechanisms during human-robot interactions. Mobile fNIRS devices allow human subjects to physically interact with robots, neuronal activity can be recorded during behavioural human- robot interaction tasks ¹⁸⁷.

1.2.1. Research Questions and Purpose

Depending on previous complex perspective of human-robot interactions and its cognitive roots in the human brain; we aimed to explore the differences and similarities between perceptual and emotional processing of human and robot faces by interpreting the hemodynamic correlates of these stimuli. For this purpose, real human face and voice stimuli and custom designed robot face and voice stimuli were presented to participants in our experimental design and their hemodynamic responses were recorded with an fNIRS instrument which had a probe covering the prefrontal cortex.

We employed fNIRS neuroimaging method to how human and robot stimuli and their congruent and incongruent face and voice pairs were altered hemodynamic response in PFC. After the experiments, participants rated human and robot stimuli based on the strength of the unpleasant feelings produced. Evaluating behavioural and hemodynamic response to robot and human stimuli may reach us to deeper understanding on cognitive mechanisms of human-robot interactions.

2. LITERATURE REVIEW

2.1. Uncanny Valley Phenomenon

The word uncanny has very rich meanings in many dictionaries: “Strange or mysterious; difficult or impossible to explain”, “Seeming to have a supernatural character or origin, eerie”, “Strange, difficult to explain”¹⁵⁻¹⁷. The term of uncanniness was first used by Ernst Jentsch in 1906 and basically expressed with “intellectual uncertainty”¹⁸. Sigmund Freud improved this concept with the “Das Unheimliche” essay and claimed that dolls and waxworks could be create ambiguous emotions and eeriness¹⁹.

Uncanny valley concept was first proposed by Japanese professor of robotics, Masahito Mori in 1970. His “Uncanny Valley Hypothesis” suggests that humanoid objects which materialize virtually, but not exactly like real human beings elicit uncanny feelings of eeriness and revulsion in observers. He used a hypothetical curve to describe this relationship, and indicated a sharp dip in this curve at almost human-like levels as an uncanny valley² (Figure 2.1).

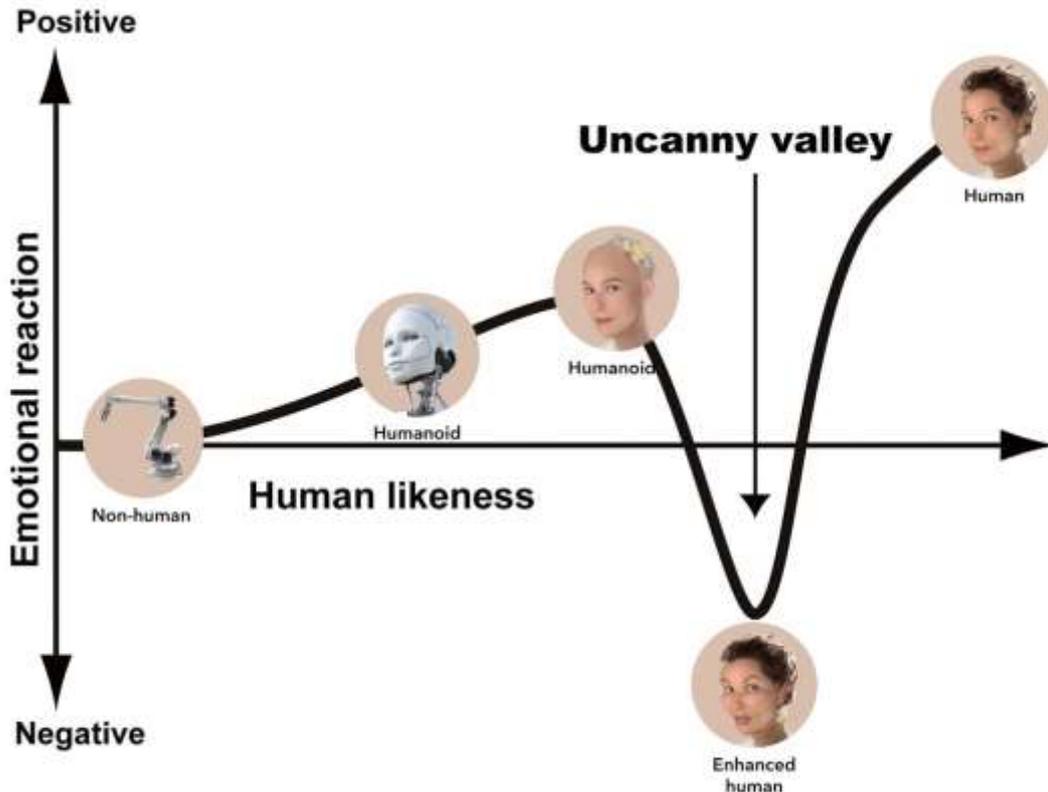


Figure 2.1: Human and robot designs are placed in uncanny valley phenomenon graph²⁰.

Mori focused on robots, mechanical devices and prostheses to explain “Uncanny Valley Hypothesis” in the early 1970s. But in the last two decades, as computer animated faces and human images have been created, this topic has gained meaning in different research areas ²¹. “Uncanny” means strange or mysterious, so it is interesting that humans have mysterious feelings about robots, which is a technological object.

Uncanny valley phenomenon is not just an interesting topic about human-robot interactions. As humans perceived this uncanny valley effect from human-like robots, animation movies and computer games, more questions will be delivered. Can we create better designs of robots and animations to be perceived more human-like? If one day, thanks to enhanced and high aesthetical designs, will we reach real human level and exceed the uncanny valley effect? Why humans are unique living creatures and robots are not? For the answer of these questions, we have to focus on the fundamentals of human psychology again because it seems that the increase in our knowledge about this phenomenon will not only help us better explain some contemporary debates such as the social cognition or theory of mind, but it will also provide us with an important tool for investigating these not yet clarified psychological phenomena. Therefore, this phenomenon is not only today’s problem, it has to involve strong psychodynamic basics ²².

2.2. Anthropomorphism

The word anthropomorphism is derived from two words in Greek language: “Anthropos” means human and “morphe” means form ¹⁵. People have a universal and innate habit to attribute humanistic skills, traits and features to non-human objects, animals and abstract objects ¹⁶. Anthropomorphism is a high-level brain function and affined with abstract thinking.

From the early ages of history; humans widely used anthropomorphic figures in art, religion, mythology and literature (Figure 2.2). Ancient Greek gods with humanistic personalities, life lessons from animals in fable stories and mascot figures of companies are different examples about anthropomorphic skills of human creativity ²³. In the modern world; computers and robots are the latest complex pieces of human creativity. Their complex structure and high computation capacity are the challenge to human brains cognitive skills. This conflict leads to many unanswered questions and gives birth to new research topics in human-computer and human-robot interaction studies, including uncanny valley studies.



Figure 2.2 : Anthropomorphism of fruits in human face form, Giuseppe Arcimboldo, Vertumnus, 1589²⁴.

2.3. Uncanny Valley in Popular Culture

Word of robot was first used by Czech playwright Karel Capek in 1920 and derived from the words robotnik and robota, which means “forced and compulsory workforce” in Czech language¹⁵. From primordial industrial robots to near human looking advanced androids, different types of robots have been part of our life since the late 20th century. Parallel to the widened use of robots in our daily lives, the robots are represented in various formats in science fiction literature, movies and several popular culture media.

Remarkable examples of uncanny valley effect can be seen in animation movies. Actor Tom Hanks’s digitally designed replica was used in the animated movie Polar Express. In spite of advanced design technology of the year 2004, digital human designs are perceived as creepy and uncanny by children and other audiences²⁵ (Figure 2.3 A). Later animation movies of Beowulf, A Christmas Carol and Tintin were criticised for uncanny designs of humans²⁶ (Figure 2.3 B). The 2019-2021 animation series of Love, Death & Robots used state of the art techniques to digitally replicate real humans (Figure 2.3 C). But enhanced realism levels of human design confuse audiences if they see

humans animation or real human in the movie and creates a novel uncanny valley effect²⁷.

Primitive humanoid robot Asimo was created in 2000. Walking with slow steps and hand waving and head motion perceived as near-human despite Asimo's primordial look²⁸. Since then, several humanoid robots with more realistic looks and advanced capabilities were produced. Lead human-robot interaction researcher Hiroshi Ishiguro, created his robot twin and named it as "Geminoid HI-1" (Figure 2.3 D). This very special humanoid robot's look was copied from its creator Ishiguro's body and has remote control capabilities. Geminoid HI-1 can speak, have basic facial mimicry and body motions. Its main purpose is to replace Ishiguro's social identity with remote control of Ishiguro. Geminoid HI-1 interacted with people in real-life conditions, and human responses varied from positive to uncanny^{29,30}. Recent humanoid robot "Sophia" has attracted the attention of the media and its sophisticated sentences with robot look trigger uncanny feelings in humans³¹.



Figure 2.3: Uncanny valley examples. (A, B, C) Human designs from Polar Express, Tintin and Love, Death & Robots animation movies³²⁻³⁴ (D) Hiroshi Ishiguro and his artificial twin Geminoid HI-1

2.4. Explanations of Uncanny Valley

Wider research areas like anthropology, philosophy and psychology work on the explanations of uncanny valley phenomenon with specialized perspectives. Cognitive, evolutionary and psychodynamic processes attend this phenomenon in various ways. Although the uncanny valley phenomenon has emerged just for recent decades, it can be rooted in primal human emotions. There are several explanations about this phenomenon.

First type of explanations prioritises perceptual mechanisms as the cause of this phenomenon. Pathogen avoidance hypothesis, Mortality salience hypothesis and Evolutionary aesthetic hypothesis assert stimulus driven, early responsive perceptual processes generate this phenomenon. Second type of explanations such as Violation of Expectation hypothesis, Categorical Uncertainty hypothesis and Mind Perception hypothesis explain uncanny valley phenomenon with more complex cognitive mechanisms. They assert late and top-down processes play a role more in this phenomenon²².

2.4.1. Perceptual Explanations

2.4.1.1. Pathogen Avoidance Hypothesis

Disgust is an evolutionary reaction to unhealthy appearance. In this point of view, human replicas which trigger uncanny phenomena may reveal a diseased person. Almost-human appearance of a robot can be perceived as a malformed and sick person even having a contagious disease. Evolutionary pathogen avoidance mechanisms activate and interpret this uncanny appearance as the source of a contagious disease³⁶. As a result, humans feel disgust as a defence mechanism to the uncanny appearance of almost human robots.

2.4.1.2. Evolutionary Aesthetics Hypothesis

Almost all human replicas or robots fall short in presenting sufficient realistic human-like features. Replica's physical attributes such as fitness, fertility, and health fail to satisfy our expectations from a real human. Thus, replicas have a low attractive appearance to us, this can lead to uncanny phenomena³⁰. Hanson (2006) tested this hypothesis with a morphed image of faces. As he improved the aesthetic properties of virtual faces, uncanny phenomena had disappeared progressively. Aesthetic properties of

faces have some features such as realism and attractiveness, but which one primarily plays an uncanny phenomenon is still unclear.

2.4.1.3. Mortality Salience Hypothesis

The Mortality Salience hypothesis, inspired by Terror Management Theory in social psychology, posits that some human replicas are uncanny because they remind people of death and trigger defence systems that cope with the deeply rooted anxiety for mortality. Indeed, many or most of humanoid replicas, such as dolls, clowns, mannequins, wax figures, zombies, and humanoid robots resemble dead individuals who have seemingly come alive ³⁷.

2.4.2. Cognitive Explanations

2.4.2.1. Violation of Expectation Hypothesis

Uncanny valley had been tested with various types of mismatch modals. Incongruence between face and voice stimuli, appearance and motion mismatch can cause this phenomenon ^{37,38}. Discomposed face structure with asymmetrical ear, nose and mouth perceived with uncanny feelings ³⁹. These examples of perceptual mismatch create conflict in our minds. People have a bias to see the human body with proper and complete condition. As a result, transformed and skewed representation of the body harms our expectations about human form. Supportive studies mainly focus conflicts on human body form, but also violation of android imagination is a possible cause. Not only crushed expectations about “human form” which perceive a human body-android features object; androids with human body parts object can crash “android imagination” ⁴⁰. In brief; violation of the expectation hypothesis stands on this bilateral conflict about human and android forms.

2.4.2.2. Cognitive Dissonance Hypothesis

If a person has contradictory ideas, moral values or beliefs and tries to take action about either one of them, a contrasting situation may occur. This discomfort between contradictory ideas and actions causes a person to feel a disturbing mood and stress which can be named as cognitive dissonance. Then person efforts to resolve contradictory ideas and actions to fix disturbing mood and psychological stress ⁴¹. Humanoid robots have realistic and human-like visual and facial features; so, people tend to attribute humanistic characteristics to humanoid robots. When people distinguish the contrast between robot’s

humanistic appearance and mechanistic background; cognitive dissonance has emerged⁴². Human and robot concepts are placed in distinct sides in the human mind; interference of distinct concepts may be one of the explanations of uncanny valley phenomenon with cognitive dissonance situation⁴³.

2.4.2.3. Categorical Uncertainty Hypothesis

New and strange information from the outer world can be a problematic issue for individuals. Lack and inconsistent information arise mistrust, uncanny feelings come along with mistrust and eeriness. When people meet with human-like objects, they tend to describe them as either human related or not. They respond more positively to human-like objects than their described human-like category⁴⁴. People have a tendency to categorize descriptions of human and android forms. Ambiguous representation of human or androids break categorical boundaries. This break arises in an uncanny valley. Few studies support categorical uncertainty and this explanation of uncanny valley is still disputable.

2.4.2.4. Mind Perception Hypothesis

Robots and androids have opposite identities from humans separately from their human-like resemblance. Perception about this opposition evokes uncanny feelings. And humans question themselves on “On which basis we perceive each other as humans?”. This question has roots and strong basis with social cognition topics such as Theory of Mind⁴⁵. Humans and robots have two main distinct characters. Agency, defined as the ability to plan the future and do something. Also experience, defined as feeling ability and sense of the outer world. Through decreased agency and experience abilities, robots perceive in an uncanny way⁴⁶. Clear oppositions between human and robot forms and robot’s lack of abilities are causing blurred imagination in the human mind. This blurred imagination determines humans’ subjective experience about robots and humans recall robots with uncanny feelings.

2.4.2.5. The Dehumanization Hypothesis

Dehumanization term defined as “perceiving a person, people or group as lacking human feeling and attributes”⁴⁵. Since the 1970s, violence behaviour against minorities, moral judgment and inter group conflicts has been classified as dehumanization examples by social psychologist. Refusal of human uniqueness makes people open to violence

behaviour⁴⁷. All perceptual and cognitive hypotheses compromise on one point: Humans feel uncanny when they perceive a human-like robot or android which has a lack of humanness. Dehumanization process has a great role in the uncanny valley. Androids have special attributes that differ from other robots, their enhanced level of human likeness, realistic face and voice features and behaviour creates complex responses in humans. On the contrary to robots, androids are perceived as incomplete humans at first look. Defective human replica isn't real enough to be a human and this ambiguity leads to uncanny feelings.

Beyond this consolidative argument with previous hypothesis; this newly emerged Dehumanization hypothesis supported by electrophysiological and behavioural studies. Face recognition is a special perceptual process for the human brain; quick responses to human faces in the outer environment have evolutionary advantages⁴⁸. Specialised brain regions like fusiform gyrus, posterior superior temporal sulcus and inferior occipital gyrus activated in this rapid face response process. Face perception process has an early and late phase. Inanimate human-like objects (dolls, toys) can perceive with early process, but only real human face activates late responses in the brain⁴⁹. Robots and artificial faces perceived tend to be more human in the first phase, but late-phased sophisticated neural mechanisms detect lack of humanness⁵⁰. Inconsistency between early and late face perception phases effects the brain, so neural impressions of inconsistency situations can involve uncanny valley phenomenon.

2.5. Face and Voice Perception

2.5.1. Face Perception

Human face has a primary role in social communication⁴⁸ and facial features express unique individual information during social communication. Facial features like mouth, ear, nose and eyes and their particular portions and shapes determine our unique face view. As I write this chapter of my thesis in June 2020, wearing face masks are enforced in inner spaces worldwide because of the COVID-19 pandemic. I feel distrust and several levels of anxiety when interacting with a face masked person. This living and striking situation about covered faces reminds of the importance of facial views in social communication.

Face perception is a very complex informative process in the human brain. In the cerebral cortex, there is a specialized area in the visual cortex for face perception. Near

the ventral surface of Temporal lobe and on the lateral side of Fusiform gyrus, Fusiform Face Area (FFA) is placed ⁵¹. FFA is a part of the visual system, and can respond to objects, bodies and other things than faces. Although some clues about individual differences on non-face response, FFA is generally defined as face-selective visual cortex area which is placed ventromedial temporal cortex and lateral occipital cortex ⁵². Prosopagnosia, a disability to recognize faces is congenital and brain damage induced multifactorial disorder. Around fusiform gyrus and FFA, dysfunctionalities and abnormalities are detected in prosopagnosia patients ⁵³. Prosopagnosia disorder is a supportive phenomenon to FFA is a face-specialized area in the human visual cortex.

Face perception is a special kind of visual perception, so face perception mechanisms in the brain consist more than retinal input-based bottom-up mechanisms. Top-down mechanisms called memories, life-time knowledge and predictions contribute to visual information processing. Given this background, face perception and recognition processes occurred quickly and accurately ⁵⁴. Face templates may be encoded in high-level frontal cortex, neural signalling which sourced from prefrontal cortex can start top-down face processing ⁵⁵. From a wider perspective; facial features and whole face processing is a complex, multi-faceted and integrated process which is placed in frontal, occipital and temporal cortex ⁵⁶. Face perception is an indicator for social behaviour in animals, stronger in mammals.

From primordial mammals to primates, face perception ability correlates with social communication capacity of species. However humans have great kinds of social behaviour and high cognitive skills thereby having the most complex face perception process and a unique visual cortex area ⁵⁷. Face perception is a basic and deeply rooted process, even new-born babies respond to faces. Face-selective responses of infant's peak at the first year, then decline and stabilize ⁵⁸. After two years, face perception skills improve constantly and after adolescent ages; it reaches adult-like abilities ⁵⁹. Improvement in perception skill can be correlated with developing perceptual mechanisms in general during the maturation process.

2.5.2. Face Perception and ERP

Event Related Potentials (ERP) is the neural response which is triggered by a distinct sensory, motor or cognitive event. This specific electrophysiological response sourced from cerebral cortex and ERP is determined as an indicator for many cognitive processes like visual and auditory perception ⁶⁰. Following the presentation of a face stimulus; a large positive potential peak detected at the between 140 and 180 milliseconds. This peak is defined as Vertex Positive Potential (VPP) and it is the first defined face-selective ERP component ⁶¹. Repeated studies showed that VPP has larger latency with face stimulus than others and expands over occipitotemporal areas. And this occipitotemporal neural activity showed a negative vertex, so finally this negative ERP component which occurred between 140-180 milliseconds after face stimulus was renamed as Negative 170 (N170) ⁶².

There are some other visual stimuli dependent ERP components. C11 component peaks around 70 milliseconds and P1 peaks around 100 milliseconds, these early posterior visual components are not selective and can be detected with any visual stimulus ⁶⁰. Yet, several face and visual stimuli experiments with different conditions consistently prove that the N170 component of ERP is the earliest, robust and most reliable indicator of amplitude change between faces and non faces objects on the scalp ⁶³. Some familiar objects like cars can evoke N170 components, but latency of N170 detected is smaller than face-dependent N170 as expected ⁶⁴.

2.5.3. Face Expression and Emotions

Emotional states are strongly represented by the human face. In neural basis; emotion process contributes to face perception in FFA and temporal lobe face-sensitive areas ⁶⁵. Face perception has more specialized processing than other object recognition mechanisms. During social communication, faces give rich and intense cues about personal information. Facial gestures are located in the human face; anger, fear, disgust, sadness, surprise, contempt and joy are the seven basic facial expressions ⁶⁶. They are defined as universal and these basic expressions occur freely from cultural backgrounds of human societies. Finding universality of facial expressions is a milestone in cognitive psychology studies. This discovery broke the views that facial expressions are dependent on cultural backgrounds ⁶⁷. Facial expressions are innate behavioural signs and have very strong evolutionary roots, even other primate species have also universal facial expression

⁶⁸. Different combinations of muscle movements in the face creates facial expressions in wider parts of the face ⁶⁹. And these six basic universal types of expressions are defined as macro- expression of face ⁷⁰.

Facial micro expressions are very fast (1/25-1/5 seconds) and constitute mimics. During normal communications, micro expressions are mostly neglected. However studies showed that some highly sensitive humans can detect this and catch some clues about ways of communication ⁷¹. Facial expressions give some important clues about human behaviour and environment. Happy faces mean humans meet its basic needs and are in good environmental condition. But a disgusted face may represent life threatening situations like poison intake. These situations are based on facial expressions and are basic examples of key roles in social communication ⁷². From the modern view, emotions are placed in two bipolar dimensions as valence and arousal. In the initial emotion perception phase, valence and arousal dimensions primarily and rapidly affect perception of the human face. Then in the second phase; valence and arousal values are used as inputs in the rest of the process ⁷³.

2.5.4. Face Effect in Uncanny Valley

Virtual face designs can trigger the uncanny valley effect. A recent study suggested that the gender, facial asymmetry, skin color, hair color and realism level preserved by a virtual face are important factors determining the uncanny valley effect ⁷⁴. Subjects tend to have more positive feelings towards realistic faces than cartoon-like face designs. They prefer normal facial asymmetry and normal face proportions in face designs. Also, smooth and natural skin color were evaluated as more likeable and attractive by the subjects. Recent study showed that emotional feelings such as affinity, trustworthiness were assigned higher to realistic face designs than cartoon-like face designs⁷⁵. Atypical facial features like different shape and place of eyes and inconsistent realism levels of faces cause perceptual mismatch in subjects, this mismatch situation can reveal uncanny valley feelings ^{39,76}. Anthropomorphism level of the robot face is crucial to evaluate human-robot interactions. Previous studies have observed that anthropomorphism is highly correlated with likeability and animacy indices ⁸. In human-robot interactions, the robot face is a prominent actor of the robot's general appearance ⁷.

2.5.5. Human Voice Perception

To understand the voice perception process in the brain; first we have to look at acoustical features of vocal sourced sounds. Frequency of the sound is an important characteristic of the voice. Males have larger vocal cords and make lower frequented sounds than females and children. Lower and higher frequencies of the sound are strong clues about the sound source ⁷⁷.

Individuals can identify human voices, but this ability is far weaker than face identification. After repetitive stimuli of the same human sound, sound identification skills are improving. So, people can better identify their friends and familiar individuals ⁷⁸. Researches on sound perception revealed neuronal basis of speech recognition and perception. Neuroimaging research suggests that sound processing in the brain primarily focuses on speech recognition and underlie vocal characteristics of the speech. Temporal lobe of the cortex defined as the sound-sensitive brain part. Human speech elicits stronger neural activity than tone or noise in superior temporal sulcus in temporal lobe ⁷⁹.

2.5.6. Voice Effect in Uncanny Valley

Sound of the robot is an important point in human-robot interaction. Components like pitch, pitch range, volume, and speech rate have a role on human perception of voice ⁸⁰. Just like a validation of our natural tendencies, people have more positive attitudes toward human-like voices over synthetic voices. There has been a correlation between positive emotions and naturalness level of voice ⁸¹.

Also, in phone communication, people prefer human voice over robot voice ⁸². During the communication with a robot, people consider the robot's face and voice both. When talking with a mechanical looking robot, they expect a synthesized voice from the robot. People have a tendency to categorize agent robots or humans. When there is a mismatch between voice and face of an agent, cognitive dissonance may occur due to violation of expectations about human/robot categorization ⁸³. Due to this mismatch effect, uncanny valley effect may take place ⁴. And asynchronous lip movement and voice of gaming characters contributed to the uncanny valley effect ⁸⁴. Inconsistency between voice and social identity, gender and accent can create undesirable emotions ⁸⁵.

2.5.7. Face-Voice Mismatch and Cross Modalities

Cognitive dissonance situation may be a possible reason for uncanny feelings and incongruency between face and voice components disrupts categorical boundaries about robot and human definitions in our perception ^{3,4,83}.

Audio-visual integration of face and voice stimuli have an important role in social interactions. McGurk effect is a well-known example for incongruent visual speech ⁸⁶. Early studies show face stimuli overcome voice effect in emotional perception ⁸⁷. Visual stimuli can lead the spatial source perception ⁸⁸. But ventriloquism (a person creates the illusion that their voice is not coming from mouth) phenomenon gives some clues about audio-visual integration, voice stimuli have a greater role than face in this phenomenon ⁸⁹. More studies confirm sound dominance, in search of timing perception of audio-visual stimuli evident by subjects determining temporal localization based on auditory stimuli ⁹⁰.

Unimodal conditions of face and voice stimuli create larger responses in the brain activity than incongruent conditions ⁹¹. Yet it is an interesting point that familiar human sounds can elicit responses in face-sensitive brain areas. While familiar people's voice processed in superior temporal sulcus, additional responses detected in FFA in neuroimaging studies. FFA response to human voice derives from voice sensitive STS (superior temporal sulcus) area and this situation may show cross-modal cooperation of sound and face perception in the brain ⁹². This cross-modal processing of voice and face has a neural basis. An advanced fMRI (functional magnetic resonance imaging) tractography study shows structural neural connections between STS and FFA. Face fusiform area has stronger connections into middle and anterior STS regions ⁹³.

Visual and auditory perception information are shared in the multimodal neural process. In person recognition tasks, multimodal areas in the left angular gyrus and right hippocampus are activated in addition to unimodal STS and FFA regions ⁹⁴.

2.6. Prefrontal Cortex

2.6.1. Introduction to Prefrontal Cortex

In the human brain, Prefrontal cortex (PFC) is located in the anterior end of cerebral hemispheres. PFC is not a unique and single region, it can be more accurately defined as the total structure of related functional areas ⁹⁵. Frontal parts of the cerebral cortex mainly responsible for high level cognitive processes like executive functions, planning, decision making and short-term memory. Emotional regulation, moderation of social behaviour and personal traits are also specialized in PFC and its subparts ⁹⁶. To perform high-level executive functions; PFC areas of cerebral cortex receive neuronal projections from thalamus, mediodorsal nucleus ⁹⁷.

Executive functions have great roles on personality and stability of individuals life, actions and behaviours are planned with all aspects in this part of Cerebral cortex. Orchestration of thoughts, emotions and behavioural responses are specialized neuronal activity of PFC ⁹⁸. Several Brodmann Areas (BA) which are located in PFC are responsible for high level cognitive functions like language ability. Language ability is a key factor to let humans develop social interactions and can live together in larger social groups. Unlike from other animals, humans can change and reconstruct their natural environment. This ability creates the basis of unique human cognition ⁹⁹.

PFC is not only the sensory or motor cortex of the brain. PFC can collect instant neuronal inputs from several cortical areas in the brain. Perceptual cues from the outer world are processed and proper social and behavioural responses are created in PFC. This integration from different cerebral cortex areas is very unique for PFC and higher-order executive functions are built on these neuronal integrity basis ¹⁰⁰.

Ventral tegmental area (VTA) and locus coeruleus (LC) are the primary sources of neurotransmitter dopamine and norepinephrine in the PFC ¹⁰¹. Working memory functions of PFC directly link to dopamine and norepinephrine levels. Dopamine is the main neuromodulator of organizing goal dependent behaviour and cognitive control mechanisms in PFC areas of the human brain¹⁰². Neurotransmitter acetylcholine is also important in high level cognitive functions. Visual attention experiments in rats showed task-related increased acetylcholine levels ¹⁰³.

2.6.2. Functional Neuroanatomy and Subregions of PFC

Phineas Gage, a railroad worker, hit an iron piece from his head in a construction accident. Iron piece crushed his orbitofrontal lobe but he could recover from head injury with primitive medical treatments of 1848. After the accident, he had lived 12 years more but his personality changed totally and he transformed into a rude and disoriented man from a respectable husband and worker. His broken personality with frontal lobe damage had started on localization of brain activity studies for the first time¹⁰⁴. Since this time; PFC and subregions have been studied in many of cognitive neuroscience experiments.

Comparative neuroanatomy and neuroimaging research assume that proportional size of PFC is relatively higher than other primate species. PFC is the largest part of the human brain and approximately covers %25-30 of all cortical areas⁹⁵. Development studies on the human brain shows prefrontal enlargement may not fit in allometric growths ways of other primates and its high volume is a notable evolutionary outcome. Complex social interactions of humans and language ability, human cognition and cultural traditions and identity are unique cognitive skills for humans and can't be mimicked by bonobos and chimpanzees which are humans closest living primate relatives¹⁰⁶. Primary visual cortex and frontal motor areas have similar sizes in both humans and chimpanzees; but human PFC has 4 times volume than chimpanzees PFC (Figure 2.4). Variety of social cues, language ability and advanced multimodal sensory information allows more complex information processes and PFC enlargement⁹⁵.

In addition to volume enlargement; some distinct parts are uniquely developed in human PFC such as Brodmann Areas and Dorsolateral PFC. These areas are distinct for functionality and morphologically to human PFC¹⁰⁷.

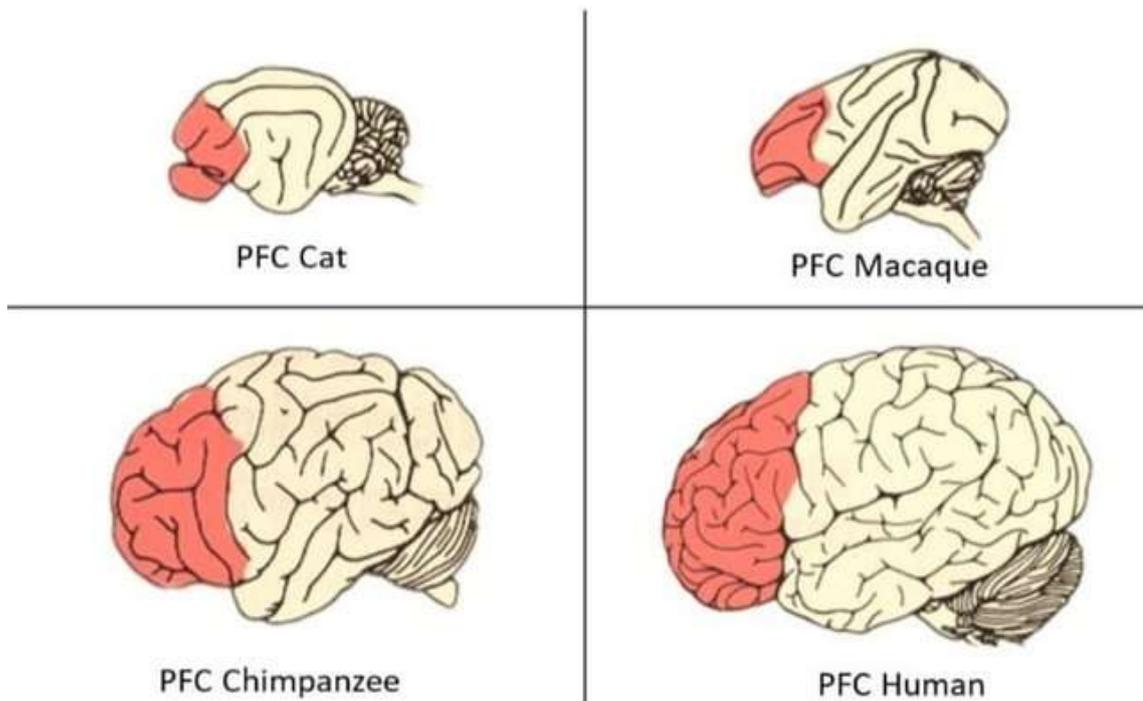


Figure 2.4: Comparison of the PFC size of human and other species ¹⁰⁸.

PFC has two main parts as Ventromedial PFC (vmPFC) and Lateral PFC(LPFC). These two main parts have different functional and morphologic specialty and have distinct evolutionary roots. vmPFC is an older part of the brain and present in all mammalian animals. But LPFC is an evolutionary advanced structure and present only in primate groups ¹⁰⁹.

Ventromedial PFC has two subparts as Medial and Ventral. These subparts cover 8 Brodmann areas as BA 11, BA12, BA13, BA14, BA24, BA25, BA32 and BA35. Lateral PFC has two subparts as Dorsolateral and Ventrolateral (Figure 2.5). These subparts cover 7 Brodmann areas as BA8, BA9, BA10, BA44, BA45, BA46 and BA 47 ¹¹⁰. Ventrolateral PFC's BA 45 is also a part of Broca's area, which has functions of human speech ¹¹¹.

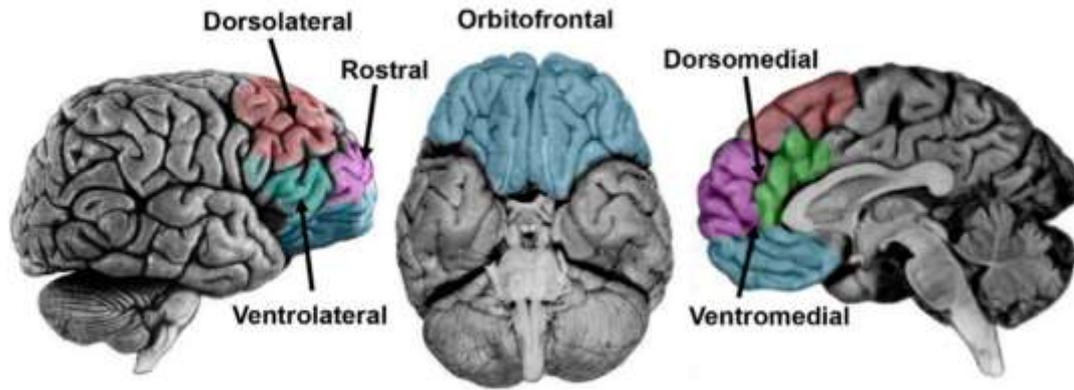


Figure 2.5 : Anatomical map of PFC subregions with different colors ¹¹².

2.6.2.1. Dorsomedial PFC

Dorsomedial PFC (dmPFC) is located at the top sides of cerebral hemispheres and it involves some portions of Brodmann Areas 8, 9, 10, 24 and 32. dmPFC is described as the core point of social brain and identity, sense of self mechanisms is processed in this subdivision of PFC ¹¹³.

Sense of self concept contains personal traits, moral values, personal beliefs and collection of characteristics. Neuroimaging research supports dmPFC roles on sense of self. Performing another role than self-identity may impair dmPFC activity temporarily, fMRI studies on actors with long practice acting careers shows relative inhibition of dmPFC areas ¹¹⁴. In parallel to self-sense researches; dmPFC impairment is detected in borderline disorder which characterize disassociation of personal identity ¹¹⁵. Social judgments and prejudices about someone may code in dmPFC. When dmPFC is stimulated with a Transcranial Magnetic Stimulation device; prejudices and social impressions are changed ¹¹⁶. Advanced social capabilities like moral values and altruistic behaviours are also linked with dmPFC ¹¹⁷.

2.6.2.2. Ventromedial PFC

Ventromedial PFC (vmPFC) is located at the bottom side of Cerebral hemispheres. vmPFC areas are developing fast in adolescence and early adulthood years ¹¹⁸. vmPFC has strong neuronal connections with deeper brain regions like amygdala. This tied connection of vmPFC supports emotion regulation functions with amygdala ¹¹⁹.

vmPFC executes emotional reactions to different social situations. Perceptual inputs from the outer world processed in vmPFC, and specific emotional reactions and behaviours are modelled as neuronal output ¹²⁰. Emotional regulations contribute to building moral values in humans, so impairment of vmPFC shows reduction in shame and guilt feelings (Koenigs et al., 2007). Research about Post traumatic stress disorder (PTSD) also shows that vmPFC impairment roles on pathogenesis of PTSD ¹²¹. vmPFC also has some executive roles on decision making and chooses an option between ambiguous situations. Patients with brain lesions which cover vmPFC areas show reduced capacity of learning from mistakes and they can't evaluate negative results from old behaviours ¹²².

2.6.2.3. Orbitofrontal Cortex

Orbitofrontal cortex (OFC) located at the bottom and front part of the PFC. Orbitofrontal Cortex consist of Brodmann area 10,11 and 47. BA 10 parts of the orbitofrontal cortex can be named specially as Rostral PFC ¹²³. OFC also shared mutual areas with vmPFC ¹²⁴. Similar to vmPFC, OFC is primarily responsible for emotion regulation and social behaviour ¹²⁵.

OFC is a key area for reward and punishment behaviour, thanks to Ventral tegmental area neurons which produce a dopaminergic reward system ¹²⁶. Lateral parts of OFC are activated with reward and punishment expectations in social interactions. Dopaminergic reward system in OFC has tight relations with several complex cognitive functions. Experiments of decision-making process, social expectations and habitual/adaptive learning behaviours show meaningful OFC activity in this reward system linked tasks ¹²⁷. OFC is also an important PFC part in psychiatric disorders. Obsessive-compulsive disorder characterizes impairment in decision making process, so hyperactivation of OFC detected with neuroimaging studies in obsessive-compulsive disorder patients ¹²⁸. Dopaminergic reward system disrupts substance use disorder and addictions. These neuronal alterations in addiction disorder show OFC dysregulation in decision making and reward behaviour ¹²⁹.

2.6.2.4. Dorsolateral PFC

Dorsolateral PFC (DLPFC) is one of the most complex parts of the human brain, and only exists in primates. DLPFC is a lately developed functional part and its maturation lasts until early adult years¹³⁰. DLPFC has rich connections with some brain parts such as thalamus, orbitofrontal cortex and hippocampus.

DLPFC has primary roles in executive functions like planning, cognitive flexibility, and working memory. Working memory is a key point for executive functions; and DLPFC is directly linked with capacity of working memory in verbal, visual and spatial tasks¹³¹. Deception and lying are examples of secondary functions of DLPFC. People with DLPFC impairment couldn't handle with conflict situations so show low performance at Stroop Test¹³². Neurotransmitters are an important component of DLPFC's cognitive functions. Acetylcholine levels are linked with working memory capacity and increased level of dopamine accelerates DLPFC maturation^{133,134}. Brain imaging studies show that structural and functional impairment of DLPFC is significant marker in clinical conditions like depression, schizophrenia and chronic stress^{121,135}.

2.6.3. Face Processing in PFC

Amygdala and PFC are the main parts of the brain for emotional face processing. Emotional stimuli, faces and social behaviours are processed with similar mechanisms in social information and face processing networks. PFC can be more activated with active face processing; cognitive tasks like face rating have more effect than passive face viewing in PFC¹³⁶. Medial parts of PFC are sensitive to happy faces, but dorsal and lateral parts of PFC can be activated with all kinds of emotional faces¹³⁷.

Humans tend to attribute mind functions to human-like agents like realistic android robots. Attributed minds to robots lead to a mind perception process in the human brain, so human-robot interactions are processed with several high level social and cognitive mechanisms in the human brain. High level PFC functions like social decision making, morality and emotional valuation role on human-robot interaction process¹³⁸. An fMRI study shows that human-robot interaction images cause increased neuronal activity in ventromedial and dorsomedial PFC areas. Human-robot interaction images lead to stronger ventromedial PFC activity than human-human interaction images in the same neuroimaging study¹³⁹. Ventromedial and dorsomedial PFC areas are responsible for social decisions, this emotional valuation and selection capabilities were tested in

uncanny valley experiment. Both ventromedial and dorsomedial PFC areas are sensitive to human, human-like and robot stimuli. Weakened ventromedial PFC activity to robot stimuli and graded dorsomedial PFC activity to human-like designs can be described as neural cues of uncanny valley in human PFC ⁶.

2.6.4. Emotion Regulation in PFC

PFC areas involve most complex human behaviours like emotion processing and regulation, social cognition and interactions, moral values and judgment. In recent years, cognitive experiments with behavioural tasks and neuroimaging studies in lesioned PFC areas reveal that complex social behaviours and emotion regulation occurs in PFC ¹⁴⁰.

Emotion regulation is a complex cognitive function and can be explained in three steps: Behaviour/experience, information processing and neuronal activity. In the experience step, perceptual cues from the outer world can be measured with emotional responses. Perceptual cues are processed and values are created in the cognitive processing step. Neuronal activities which prompt these steps can be detected with neuroimaging methods ¹⁴¹. Variety of external cues such as human voice, human face and facial mimicry are perceived by sensory organs. Perceptual signals are sent first to sensory areas in the cerebral cortex, then directed to amygdala, ventral striatum and then to PFC as the final processing location. Emotion regulation occurs primarily in three different parts of the human brain: In the first part, amygdala is the major subcortical structure for generating emotions from perceptual information. Amygdala discriminates different emotional cues in a basic dimension as positive and negative. Positive and negative dimensions are the basic valuation of emotions ¹⁴².

At the second step, Ventral striatum have several roles: Learning emotional patterns from facial cues, predict rewards or punishment from the cues ¹⁴³. Third step is the role of the vmPFC. vmPFC has the highest level of neuronal organization for integrating emotional signals from Amygdala and Ventral striatum (Figure 2.6). Two dimensional positive and negative valuations for emotional signals are created in Amygdala, these affective valuations evaluate together with executive control areas in PFC in goal-directed way ¹⁴⁴. vmPFC has basic control and modulation capabilities on emotions. Realistic and congruous expectations about emotional stimulus also created in ventromedial parts of PFC ¹⁴⁵. vmPFCs role on executes positive and negative affective valuation with goal-dependent context support with neuroimaging studies. Patients with

vmPFC lesions can't recognize relation between healthy food and healthy body in an affective picture experiment ¹⁴⁶.

Reappraisal of emotions beyond two dimensional valuations is the simplest cognitive control step during the emotion regulation process. PFC's control mechanisms on emotions involve several high-level cognitive processes such as attention, memory and cognition ¹⁴⁷. Dorsolateral and posterior parts of PFC use selective attention and working memory capabilities to reappraisal of relevant emotional stimuli ¹⁴⁸. DLPFC's attention capacity can resolve emotional conflict situations. Neuroimaging research shows impaired DLPFC activity in major depression patients, compatible with weakened emotion regulation process ¹⁴⁹. Ventrolateral parts of PFC join the reappraisal process after the DLPFC parts. Ventrolateral PFC uses semantic memory information to select emotional stimulus in goal-based context and reorder reappraisal process ¹⁵⁰. Ventrolateral PFC's roles on emotion regulation shown with several cognitive tasks as encoding of negative emotions, inhibition and modulation of emotional responses ¹⁵¹. Attention of emotional stimuli mechanisms damages with anxiety-related behaviour, neuroimaging studies support this situation with decreased ventrolateral PFC activity in anxiety disorder patients ¹⁵².

In the summary; emotion regulation is a very complex and multilevel process in the human PFC and involves subregions of the PFC. Basic emotion modulation, inhibition and encoding process and realistic expectations from emotional information are created in ventrolateral and ventromedial parts of the PFC. But dorsolateral parts of the PFC are mainly responsible for selective attention on emotions and reappraisal of emotional information ⁵.

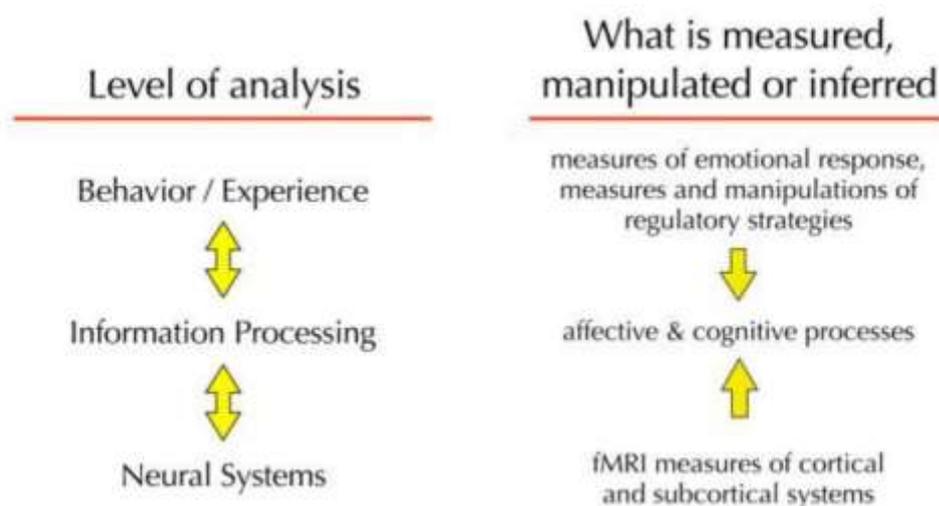


Figure 2.6 : Cognitive steps of emotion regulation ¹⁴¹.

2.6.5. Human-Robot Interactions and Social Cognition in PFC

Concept of robots has been part of our lives for years. Thinking of robot concepts creates self-generated thoughts which are independent from robot stimuli. From the cognition perspective; robots are neither human nor animal. They are not living creatures, but they can't be classified as basic mechanical devices ¹³⁵. So, anthropomorphic skills and features give special status to robots to create abstract thinking and social cognition processes in the human brain.

Primordial and mechanical look robots were first used in factories. But advances in robot technology create more sophisticated, humanistic and social robots. Social robot is a term for specially designed robots to interact with people in the natural environment ¹⁵³. Social robots make way for robots to can be used in services sectors such as healthcare, hospitality and retail. Robot nurses, robot maids and robot sellers allow humans to interact with social robots in their daily life. Social robots have deeper and more meaningful impressions on humans than autonomous cars or robot arms in factories. So, interaction with social robots is a complex and layered process and produces rich perceptual, behavioural and emotional markers for cognitive psychology studies ¹⁵³. Humans accept social robots as partners in specific goal-based actions. Humans also tend to easily accept more humanistic designed robots as partners ¹⁵⁴.

Social cognition term is involved in several cognitive processes. Humans have a sense of their own identity, be aware of other people's mind and have meaningful interaction with humans. Layered elements of social interaction which are speech, face gestures and body posture form social cognition ¹⁵⁵. Diverse and complex social interactions can build a rich structure of social cognition and better social capacities. Improved social capacity provides stronger emotional abilities and more accurate reactions to others behaviours during social interactions ¹⁵⁶. Humanistic face, voice and interaction skills give robots a diverse existence between mechanical devices and humans. Owing to their unique status, robot-human interactions are an effective source to form social cognition in humans.

Emotions are one of the core points of human beings. Human-robot interactions generate a rich emotional process which is a key point to form social cognition. Robots can trigger emotional responses such as distress, happiness and trust in humans ¹⁵³. Appraisal theory of emotions can be adapted to model affective responses to robots. According to appraisal theory, there is a causal link between cognition and emotion ¹⁵⁷.

Appraisal variables of emotion consist of external cues as robot faces, voices, behaviour and internal judgments as prejudice and memories about robots. Cognitive and affective responses during human-robot interaction are dynamic results of appraisal variables. Social cognition has a perceptual and attributional process. Face perception is a special step of social perception. Emotions are constructed from perceptions and evaluations during social interactions¹⁵⁸. Emotion appraisal and attribution of perceptual clues has occurred in the human PFC¹⁴⁰.

Sense of self and being aware of other human's mind ability is the core point of social cognition. Dorsomedial PFC is a specialized part of the human brain which is responsible for the sense of self and understanding others mind¹⁵⁹. Like other high-level cognitive functions, abstract thinking is occurs in the PFC. Brodmann 10 areas of the orbitofrontal cortex are named as the rostral PFC. Rostral PFC is the brain area which is primarily responsible for assessment and execution of abstract rules and moral values, reasoning and abstract thinking process¹⁶⁰.

2.7. fNIRS Neuroimaging Method

fNIRS (Functional Near Infrared Spectroscopy) is a neuro-imaging method, based on cerebral hemodynamic responses. fNIRS use near-infrared light to measure hemodynamic responses which depend on cerebral activation or deactivation. In spectroscopy technique, substance matter and electromagnetic radiation interacted. This matter-electromagnetic radiation interactions can be measured with wavelength and radiation frequency¹⁶¹. fNIRS method based on this brain tissue-Near Infrared light (NIR) interaction. fNIRS method can also be named as optical topography, diffuse optical imaging and NIR.

Pulse oximetry method is a very simple and non-invasive technique for the measurement of Oxygen saturation in peripheral tissue. Its working mechanisms can be a primary example of fNIRS technique: Two light sources aim the tissue and their absorption and reflection levels specify the oxygen saturation¹⁶². From the early 1980s, pulse oximetry was widely used in clinical trials as the easiest method to indicate oxygen saturation of peripheral tissues¹⁶³. Following developments of NIR use in detecting oxygen saturation; transparency of brain tissue to NIR light was discovered in 1977¹⁶⁴. It was the first step to develop NIRS devices; several teams worked to invent the NIRS method in the late 1980s. After the use approval from Federal Drug Administration, first commercial fNIRS device INVOS 3100® produced¹⁶⁵. In Japan; research groups also

studied NIR light-brain tissue interactions in the 1990s and they derived the term Optical Topography ¹⁶⁶.

2.7.1. Working Mechanisms of fNIRS

Cerebral blood flow can be changed with cognitive tasks with several neurophysiological mechanisms. Autoregulation and neurovascular coupling mechanisms have executive roles on cerebral blood flow during neuronal activation. When a distinct brain region is activated with a cognitive task; neuronal and glial metabolism also boost and they are beginning the depletion of blood flow. With neurovascular coupling mechanism; Cerebral blood flow to the activated neuronal area has to be increased soon. Cognitive task dependent neuronal activity involves enhanced cerebral blood flow in specific brain regions. This secondary hemodynamic response to primer neuronal activity with neurovascular coupling mechanism is the basic principle of fNIRS method ¹⁶⁷. Hemodynamic response starts 1-2 sec after primer neuronal activity and after the 5-6 secs of external stimuli hemodynamic response peaks. After the peak, hemodynamic response steps back and blood levels depletes in the neuronal tissue. Hemodynamic response activity can be called as BOLD (Blood-oxygen level dependent) and BOLD signals are markers of specific stimulus in neuroscience studies with fNIRS method ¹⁶⁸.

fNIRS is a non-invasive method and only uses Near infrared light to measure cerebral blood flow in microvascular structures like arterioles, venules in specific brain regions. Infrared light interaction to brain tissue has several types as transmission, reflection and absorption. fNIRS method uses near-infrared light (700-900 nm spectral interval) to detect oxygenated hemoglobin (oxy-Hb) and deoxygenated-hemoglobin(deoxy-Hb) in red-blood cells. Near-infrared light has a transparent effect to skin, bone and muscle tissues but Hb and deoxy-Hb are not transparent and they have strong absorbance to Near-infrared light in 700-900 nm wavelength (Figure 2.7). This optical window of fNIRS light ensures transmission from skin, bone, tissue but absorption from hemoglobin and deoxygenated-hemoglobin ¹⁶⁹.

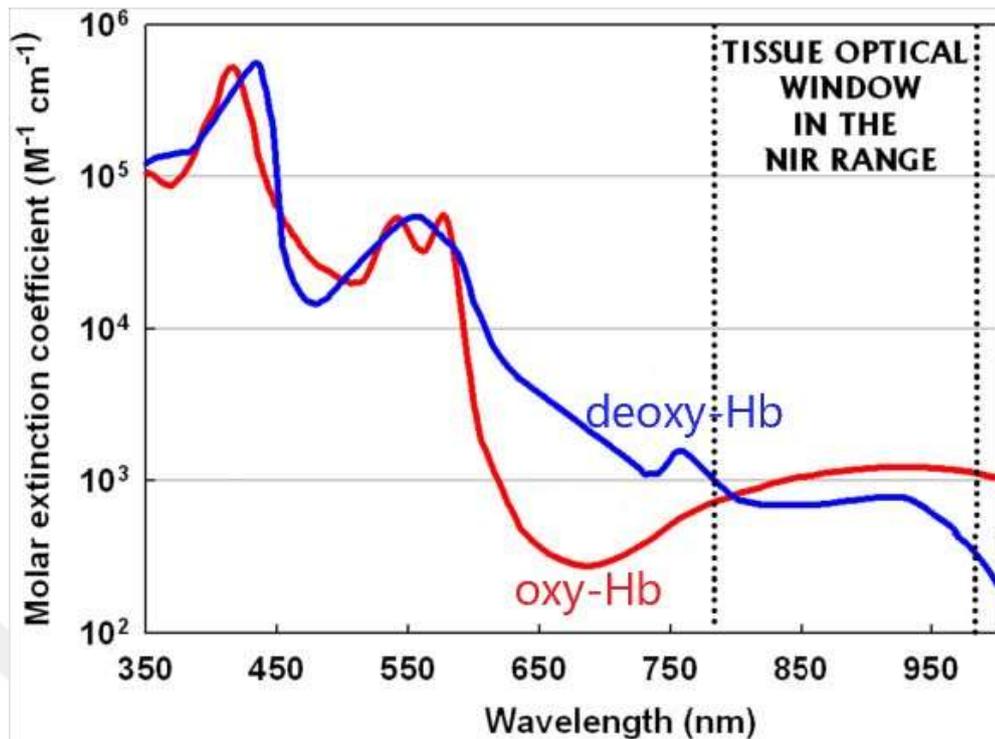


Figure 2.7: Optical window of NIR light ¹⁷⁰ .

Chromophore molecules can absorb light at certain spectral intervals. Oxyhemoglobin and deoxyhemoglobin molecules in red blood cells have chromophore characteristics in the optical window of NIR light. 700nm-900nm interval of NIR light interaction on Oxyhemoglobin-deoxyhemoglobin chromophore concentrations can be calculated with Modified Beer-Lambert law. oxy-Hb and deoxy-Hb chromophores are measured with two different wavelengths. Modified Beer-Lambert law explains this situation on two grounds: Absorption of NIR light in red blood cells is changed equally and loss level of NIR light distribution is consistent ¹⁷¹ .

Two and more different wavelengths create a better optical attenuation signal of fNIRS. Objective calculation with Modified Beer-Lambert law provides more accurate detection of NIR lights optical signal. There are several physiological noises in the fNIRS method. Major noises are 3 seconds period of breathing, mean arterial blood pressure, 10 second period of heart rate fluctuations (which are named Mayer waves) and blood flow in arterials and venules in the scalp ¹⁷² . Calculation of optical attenuation of NIR light with Modified Beer-Lambert law ensures minimising the artifact and physiological noise levels in fNIRS measurement ¹⁷³ .

Hemodynamic responses which are detected by fNIRS method can be classified as main groups ¹⁷⁴. There are three different procedures in fNIRS method as continuous wave, frequency domain and time domain depend the types of hemodynamic response:

- Is source of hemodynamic response as intracerebral or extracerebral?
- Is hemodynamic response task based(evoked) or spontaneous(non-evoked)?
- Is origin of hemodynamic response mainly from cortical neurons or physiological artifacts?

2.7.1.1. Continuous Wave (CW)

CW is the most common and basic method in fNIRS measurement. It is very sensitive to cerebral blood flow changings and instant sampling rate can be precise as milliseconds. CW has the simplest tissue spectroscopy mechanism. Continuous NIR light illuminates red blood cells and levels of NIR light absorption by oxy-Hb and deoxy-Hb chromophores are measured. In continuous wave fNIRS systems, NIR light sources have constant frequency and amplitude over the time. One light is to illuminate and another light is to detect, two NIR lights in different wavelengths are used. CW can't detect absolute absorption level of oxy-Hb and relative changes of oxy-Hb can be measured. Optical attenuation of oxy-Hb/deoxy-Hb chromophores and NIR light is calculated with Modified Beer-Lambert law in CW procedure. Two different light waves between 700 and 900 nm (within the optical window of the fNIRS device) were used in Continuous wave procedure. Emitting and incident light to tissue is called a "source" and detecting light after absorption is called a "detector" (Figure 2.8). Source and detector lights are paired with each channel in fNIRS device ¹⁷⁵.

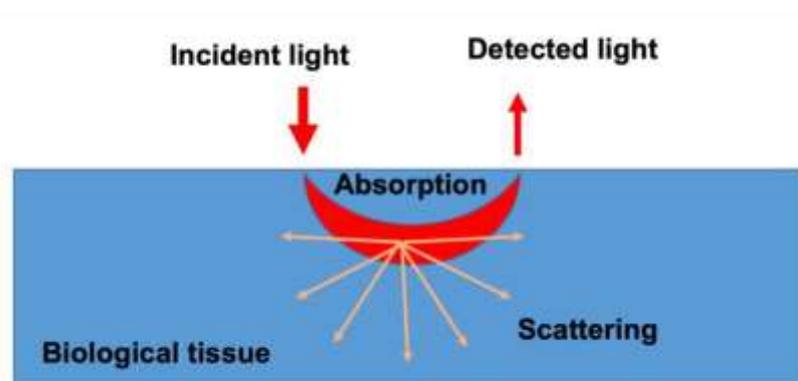


Figure 2.8 : Absorption and scattering of Near Infrared light ¹⁷⁶.

2.7.1.2. Frequency Domain

In this fNIRS method; NIR light's amplitude has sinusoidal oscillations near 100 megahertz. This amplitude modulated NIR light system can detect absolute absorption levels of oxy-Hb. But amplitude modulated NIR light sources and frequency oscillation systems are very complex and more expensive. Frequency domain fNIRS method mostly applied with immobile devices¹⁷⁷.

2.7.1.3. Time Domain

Time Domain fNIRS method works with NIR light pulses consecutively around 70 picoseconds. This method provides low temporal resolution and less wavelengths. This method is also more expensive and involves immobile, technically complex devices¹⁷⁶.

2.7.2. Comparison of fNIRS with Other Neuroimaging Methods

In modern neuroscience; several methods are used in cognitive and clinical experiments besides the fNIRS method. Functional magnetic resonance imaging (fMRI), electroencephalography (EEG), magnetoencephalography (MEG) and positron emission tomography are the major methods in wide areas in brain research (Table 2.1). PET methods use radioisotopes to scan tissues; radioactive and harming effects of radioisotopes on health limit PET methods to use in experimental research¹⁷⁸. MEG devices are technically complex, very expensive and have high operational cost. Thus, the MEG method isn't a primary option for cognitive and neuroscience experiments¹⁷⁹.

fNIRS and fMRI methods have some common neurovascular coupling working mechanisms. Both techniques are based on hemodynamic brain responses to specific stimuli. fMRI signal has longer hemodynamic responses measured with 1-5 seconds but fNIRS signal has rapid hemodynamic responses up to 1 second. fMRI has advantages on spatial resolution, it is allowed to measure neuronal activity in subcortical structures and whole brain areas with accuracy in millimetres. But fNIRS signal can penetrate 1.5-2.5 centimetre below the cortical surface and its accuracy is up to 1 centimetre from the neuronal source¹⁷⁰.

fNIRS devices are portable, EEG devices are similar in this point. Both fNIRS and EEG methods have low operational cost and lower device cost than fMRI method. fNIRS has better spatial resolution than EEG method, it can detect neuronal activity within 1 centimetre but EEG method localize activity within 2-3 centimetres accuracy.

EEG can detect deeper cortical structures than fNIRS. EEG has the highest temporal resolution in neuroimaging methods within milliseconds, which has better accuracy than fNIRS method ¹⁸⁰. Fast occurring cognitive events like Stroop task can be detected with EEG owing to its instant capture capacity of neuronal activity. Due to hemodynamic response occurring 1-2 sec after the stimulus, fNIRS is a convenient method for slow occurring emotion and perception tasks ¹⁸¹.

fNIRS method can be combined with EEG technique in multi-modal neuroimaging studies. In recent years, a body of clinical and cognitive studies use fNIRS and EEG methods simultaneously in the same experiment design. Brain-computer interface research also involves fNIRS-EEG integration modals. fNIRS-EEG integration combines advantages of both techniques and minimises limitations, so it promises advanced neuroimaging methods in experimental research ¹⁸².

fNIRS is a preferred neuroimaging method in developmental studies with infants. fNIRS method fits in the natural environment of subjects with portable and silent structure. fNIRS cap is easier to place on the scalp than EEG cap. fNIRS methods also tolerate motion artifacts better, infants can feel comfortable during fNIRS research. Its portable and silent structure allows different auditory and visual experiments in both infants and every age group of subjects. Technical and design improvements on advanced fNIRS devices are ongoing ¹⁸³.

fNIRS method has a better tolerance to head motion artifacts, so more various cognitive tasks like verbal and speech experiment, cognitive tasks with children and infants can be arranged with fNIRS method. fNIRS is a convenient method to record brain activity in a subject's natural environment. Even driving and cycling tasks can be recorded with fNIRS method owing to its tolerance on body motion artifacts ¹⁸⁴. Ecological validity is an important factor for psychological experiment settings in which fNIRS methods present advantages over fMRI and EEG methods ¹⁸⁵. But lower temporal resolution than EEG and lower spatial resolution than fMRI are disadvantages of the fNIRS method. fNIRS method is sensitive nearly 2 cm below the cortical surfaces, thus it has limitations with superficial cortical areas.

Table 2.1: Comparison of fNIRS method with other Neuroimaging methods

	fNIRS	EEG	fMRI
Spatial Resolution	Moderate resolution with 1 centimetre and limited with 1.5-2.5 cm below the cortical surface	Low resolution with centimetres and limited with 5 cm below the cortical surface	High resolution with millimetres, can reach whole brain areas
Temporal Resolution	Moderate with up to 1 second	High with milliseconds	Low with 1-5 seconds
Cost	Low	Low	High
Preparation time	Low	High	Low
Sensitivity to movement	Low	Moderate	High
Mobility of equipment	Mobile	Mobile	Fixed structure
Ecological validity to Subject's Natural environment	High	Moderate	Low
Age range of Participants	Infants, Children and Adults	Children and adults	Preferred to adults

2.7.3. fNIRS Method in Neuroscience and Uncanny Valley Studies

fNIRS method is an easy tool for an experimental design, has limited exogenous noise and is suitable to collect more robust data and presents more natural environment to subjects in an experiment setting ¹⁸⁶. These are the advantages of the use of fNIRS cognitive task paradigms. Several types of audio-visual stimuli such as smiling faces, negative valence video clips, and emotional content video clips are shown to subjects in different experiments with fNIRS neuroimaging method. Altered level of hemodynamic responses in PFC and subgroups are detected with fNIRS in these different experiments ^{187,188}.

A wide fNIRS study with neutral and fearful pictures, early emotion induction and late emotion regulation mechanisms are investigated. Increased bilateral PFC activity was detected with emotion induction, but top-down emotional process and regulation can also

occur lately and top-down process affects left PFC areas ¹⁸⁹. The uncanny valley effect has some complex responses in perceptual and processing steps, these top-down mechanisms in left PFC may be involved in uncanny valley effect.

fNIRS is an appealing method for PFC studies in many aspects, for instance to search anatomical locations of emotional responses in PFC and sublocations of PFC and to study the neural mechanisms in the emotion-action interaction processes. Mood-cognition experiments, and emotion with executive functions have been both studied with the fNIRS method ¹⁹⁰. Subjects were exposed to artistic and inartistic stimuli in a visual tasked fNIRS study. Artistic stimuli triggered a more robust hemodynamic PFC response with fNIRS method ¹⁷². If aesthetic and pleasant dimensions of visual stimuli reveal more robust PFC activation, we can expect significant PFC activity with our well-designed robot and human visual stimuli.

We have auditory stimuli as robotic and human voices in our uncanny valley experiment, some fNIRS researches investigate emotional human voices in PFC sub regions ¹⁹¹ and search how emotional words create responses in frontal cortex and lateralization ¹⁹². fNIRS method preferred in human-robot interaction studies between human subjects and embodiment robots. Mobile fNIRS devices allow human subjects to physically interact with robots, neuronal activity can be recorded during behavioural human-robot interaction tasks ¹⁹³.

In a recent uncanny valley experiment, real faces and computer-generated artificial faces were studied with the fNIRS method. They mainly focused on lateral orbitofrontal cortex (IOFC), and they found that computer generated faces trigger less hemodynamic responses compared to real faces in IOFC. And they also detect those computer-generated faces have less activation in the recognition and appraisal process. In this uncanny valley experiment, emotion regulation mechanisms like value appraisal and emotion recognition are studied in IOFC. In accordance with our audio-visual uncanny valley experiment, they found speech cues from computer generated faces have a clear effect on emotion recognition process ¹⁹⁴.

Another uncanny valley study which their visual stimuli is very similar to ours as human-like and robotic visuals, focused on anterior PFC activity. They asked participants to human likeness and eeriness of robotic and human visuals like our experiment. They found increased hemodynamic activity with fNIRS on high-arousal visuals as expected. More importantly, they detected increased PFC activity with near-human visuals and near-robot visuals ¹⁹⁵.

Based on the previous experimental studies, we can accept that the fNIRS neuroimaging method is a convenient tool for uncanny valley and human-robot interaction research. In the third part of this thesis; we examined the specific hemodynamic response of the human PFC to the faces and voices of human and robotic stimuli using the fNIRS neuroimaging method.



3. MATERIALS and METHODS

3.1. Behavioural Experiment

3.1.1. Participants

Sixty adult and healthy participants participated in the study. Participants were divided into two age groups which will be referred to as the “older age group” and the “younger age group”. Each group had thirty participants. Inclusion criteria of young generation participants are:

- Between 18 and 30 years old
- Being healthy and not having a diagnosed with a neuropsychiatric disorder
- Not using neuropsychiatric drugs and treatment
- Having a normal and healthy visual and auditory sensory
- Having a college degree or being a college student
- Being digitally literate and actively using computer in daily life

Inclusion criteria of old generation participants are:

- Over 40 years old
- Being healthy and not having a diagnosed with a neuropsychiatric disorder
- Not using neuropsychiatric drugs and treatment
- Having a normal and healthy visual and auditory sensory
- Having a college degree
- Being digitally literate and actively using computer in daily life

Exclusion criteria of both generation groups are:

- Being color blind
- Having diagnosed with a neurological or psychiatric disorder
- Using any neurological agent at least 15 days before the experiment
- High alcohol consumption

The older age group consisted of 13 women and 17 men which had an age range of 40-64 ($M = 51.2$, $SD = 7.39$), while the younger age group consisted of 12 women and 18 men which had an age range of 18-27 ($M = 20.3$, $SD = 2.07$) (Figure 3.1). The study was conducted in compliance with the WMA Declaration of Helsinki, and participants signed a consent form before the experiment. Any payment wasn't made to the participants.

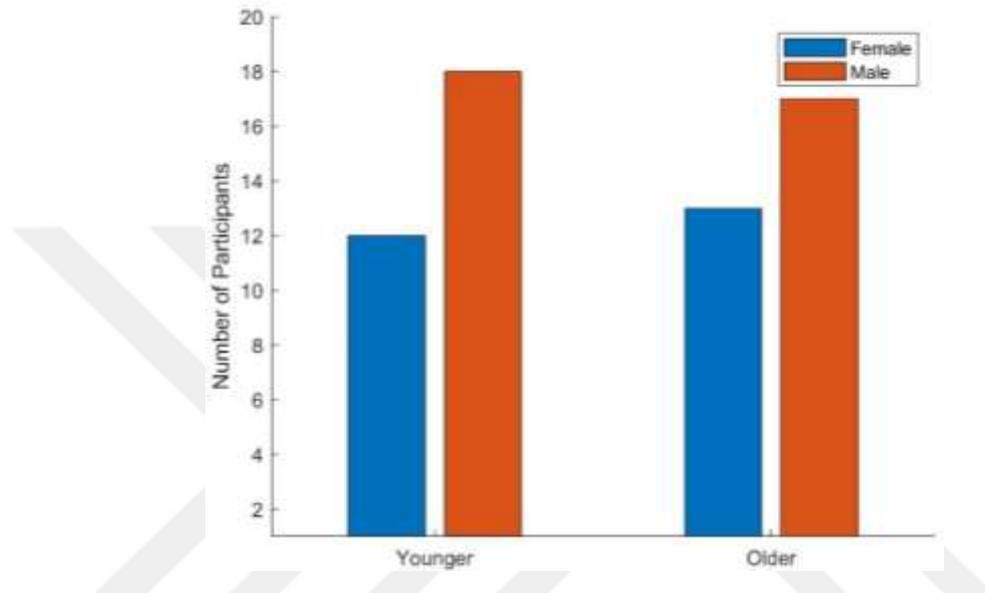


Figure 3.1: Number of participants by gender and age group.

3.1.2. Experimental Stimuli

We used 16 different stimuli in our behavioural experiment. These include 6 unimodal stimuli (3 only visual face stimuli, 3 only auditory stimuli) and 10 multimodal stimuli. Only visual and only auditory stimuli were combined with each other to create 9 multimodal audio-visual stimuli. There was also one control multimodal stimulus, so there were in total 10 multimodal audio-visual stimuli (Table 3.1).

Table 3.1: Experimental stimuli of Behavioural Experiment.

Unimodal		Multimodal
Only Visual Stimuli	Only Auditory Stimuli	Audio-visual Stimuli
		Real Face - Realistic Voice (control stimulus)
Realistic Face	Realistic Voice	Realistic Face - Realistic Voice
		Realistic Face - Semi-realistic Voice
		Realistic Face - Unrealistic Voice
Semi-realistic Face	Semi-realistic Voice	Semi-realistic Face - Realistic Voice
		Semi-realistic Face - Semi-realistic Voice
		Semi-realistic Face - Unrealistic Voice
Unrealistic Face	Unrealistic Voice	Unrealistic Face - Realistic Voice
		Unrealistic Face - Semi-realistic Voice
		Unrealistic Face - Unrealistic Voice

3.1.2.1. Visual Stimuli

As visual stimuli, we created animated faces at different levels of naturalness in the human-robot spectrum. These animations were modelled from a real human face (Figure 3.2 a) and had three degrees: A lifelike humanoid design that we call the “realistic human face”, a primitive robot design that we call the “unrealistic human face”, and a face in between that we call the “semi-realistic human face” (Figure 3.2 b-d).

The 3D models of faces were created using the Reallusion Character Creator 3® software. Default 3D human-like templates were altered to create the models used in the images and video clips. The degree of the naturalness of the faces was manipulated by altering the texture of the underlying mesh, giving surface material a glossier look. The facial animation was created using the Reallusion iClone-7 software. Mouth movements were adjusted to follow the speech simultaneously by using a software’s text-to-speech plugin. Any lack of harmony between the speech and the video were fixed manually.

The real human face stimulus was created by recording a 33-year-old male model. He had no visible body hair except his eyebrows (Figure 3.2 a). In the realistic human face, all facial features imitated a real human face with proper portions and locations. It had no body hair except eyebrows and the skin color was naturalistic (Figure 3.2 b). The semi-realistic human face had light blue eyes, sunken cheeks, apparent but colorless lips, visible ears and nose. In contrast to the realistic human face, its skin color was white. Due to this contrast between skin color and facial features, we expected a mild uncanniness effect from this design (Figure 3.2. c). The unrealistic human face had very basic facial features. The eye area had no details, the skin color was dark grey, and the mouth, the

nose and the ears were simply outlined. The surface material was metallic, bright and reflective to make the look compatible with basic robot design (Figure 3.2 d) ¹⁹⁶.

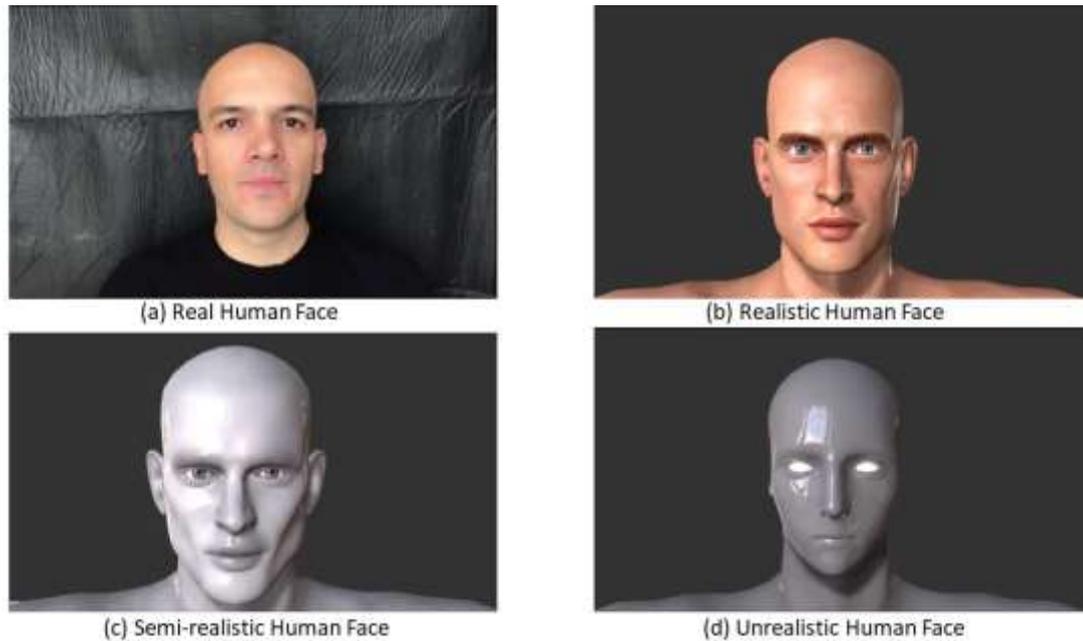


Figure 3.2: Sample static frames from the visual stimuli.

3.1.2.2. Auditory Stimuli

We recorded the voice of a 19-year-old, native English male speaker while he said the phrase “How are you, how is it going?” in a sound recording studio. This sound file was used as the realistic voice condition in our study. In addition, this sound file was modified to manipulate the naturalness of the sound in different degrees: a robotic sound that we call the unrealistic voice and an artificial sound in between the human and robotic sounds that we call the semi-realistic voice. Pitch and formant parameters of the sound (realistic voice: 3rd minor -80 formant -1.25, semi-realistic voice: 3rd minor -85 -1.25 formant, unrealistic voice: 2 minor 5 9.48 formant) were adjusted to obtain the deserved effects. All sounds had a frequency interval between 60 and 512 Hz ¹⁹⁶.

3.1.2.3. Audio-visual Stimuli

9 audio-visual video stimuli were created by pairing all three animated visual stimuli with all three types of auditory stimuli using Adobe Premiere® software. There was an additional audio-visual stimulus, namely the ‘real’ audio-visual stimulus which consisted of the real human face paired with the realistic voice. This was used as a control condition.

3.1.3. Experimental Procedure

Participants were seated in a chair in front of a 17-inch LCD screen (Samsung SyncMaster 923NW LCD monitor, 1440x900 pixel, 60 Hz frequency) in a dark room (Figure 3.3). The screen height was set to the eye level of the participants, and the distance of the participant from the screen was 45 cm^{197,198}.



Figure 3.3: Participant watched an audio-visual stimulus from the screen during the experiment.

The experiment consisted of three types of blocks: 6 blocks of the visual stimuli, 6 blocks of the auditory stimuli, and 20 blocks of the audio-visual stimuli, presented in this order. In each visual stimuli block, the realistic, semi-realistic, and unrealistic human faces were shown twice in random order. In each auditory stimuli block, the realistic, semi-realistic, and unrealistic human voice stimuli were presented twice in random order. In each audio-visual block, the 10 audio-visual stimuli described in Table 2.1 were presented twice in random order. The 20 audio-visual blocks were presented as two sets of 10 blocks, separated by an 18-sec rest.

Each trial of the experiment within each block started with a fixation screen (1.5 sec), followed by the stimulus screen (4 sec). Upon viewing the stimuli, participants were asked to rate the uncanniness of the stimuli within 6 seconds (Figure 3.4). Participants rated the stimuli using a 1-to-9-point Likert scale where 1 indicated “normal” and 9 indicated “uncanny” (Turkish translations of the words: “normal” and “huzursuz” were also placed in the rating screen). The experiment was programmed using the open source PsychoPy3 software, a Python library which has a special builder interface to conduct cognitive science experiments ¹⁹⁹.

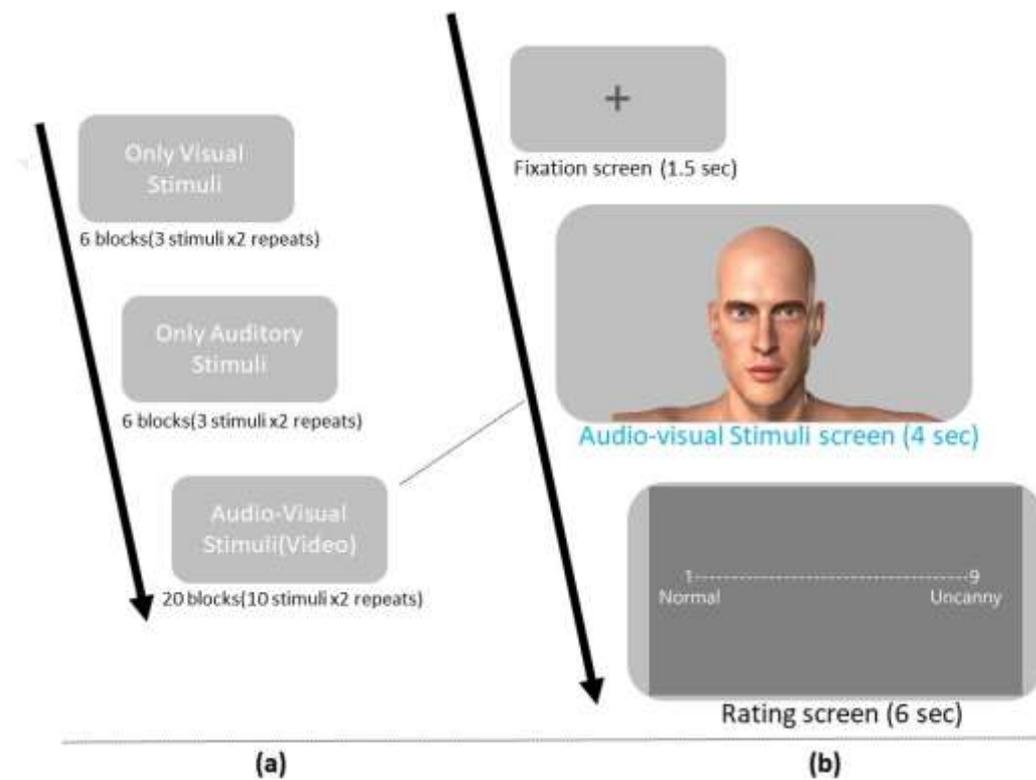


Figure 3.4: Experimental design of behavioural experiment: (a) Block structure of the whole experiment (b) The structure of a single trial.

3.1.4. Statistical Analysis

We computed the average rating score of uncanniness for each type of stimuli in the experiment and listed them in the tables. Multivariate ANOVA analyses were employed to unimodal and multimodal stimuli separately to evaluate uncanniness ratings of stimuli between age groups. Then we performed several repeated measure ANOVA analyses to test our hypotheses. These are the analyses:

- 2 (Age: Old, Young) x 3 (Naturalness: Realistic, Semi-realistic, Unrealistic) mixed ANOVA on the ratings given for the visual stimuli.
- 2 (Age: Old, Young) x 3 (Naturalness: Realistic, Semi-realistic, Unrealistic) mixed ANOVA on the ratings given for the auditory stimuli.
- 2 (Age: Old, Young) x 3 (Visual Stimuli: Realistic, Semi-realistic, Unrealistic) x 3 (Auditory Stimuli: Realistic, Semi-realistic, Unrealistic) mixed ANOVA on the ratings of the audio-visual stimuli. This ANOVA was performed to check whether the congruence of the auditory and visual stimuli has an effect of uncanny ratings.
- 2 (Age: Old, Young) x 2 (Congruency: Congruence, Incongruence) mixed ANOVA on the ratings of the congruency situation. This ANOVA was performed to check at which level congruence and incongruence face-voice pairs differ from each other.
- Omnibus 2 (Age: Old, Young) x 3 (Modality: Only Visual, Only Auditory, Audio-visual) x 3 (Naturalness: Realistic, Semi-realistic, Unrealistic) mixed ANOVA. In this ANOVA, the realistic audio-visual condition was defined as the mean rating of all conditions that had a realistic human face (i.e. realistic face - realistic voice, realistic face - semi-realistic voice, and realistic face - unrealistic voice); the semi-realistic audio-visual condition was defined as the mean rating of all conditions that had a semi-realistic human face (i.e. semi-realistic face - realistic voice, semi-realistic face - semi-realistic voice, and semi-realistic face - unrealistic voice); and the unrealistic audio-visual condition was defined as the mean rating of all conditions that had an unrealistic human face (i.e. unrealistic face - realistic voice, unrealistic face - semi-realistic voice, and unrealistic face - unrealistic voice).

All statistical analyses were conducted with open-source JASP software

3.2. Neuroimaging Experiment

3.2.1. Participants

Participant population of the neuroimaging experiment was totally different from previous behavioural experiment. 35 healthy adults participated, 6 participants were excluded from analysis because of the poor recording quality. Remaining 29 participants had an age range between 20 and 38 (age $M = 28.5$, $SD = 5.5$), which consisted of 11 females (age $M = 31$, $SD = 5.45$) and 18 males (age $M = 27.1$, $SD = 5$) (Figure 3.5). Inclusion criteria of participants to our experiment are:

- Between 20 and 40 years old
- Being healthy and not having diagnosed with a neuropsychiatric disorder
- Not using neuropsychiatric drugs and treatment
- Having a normal and healthy visual and auditory sensory
- Having a college degree or being a college student
- Being digitally literate and actively using computer in daily life

Exclusion criteria from experiment are:

- Being color blind
- Having diagnosed with a neurological or psychiatric disorder
- Using any neurological agent at least 15 days before the experiment
- High alcohol consumption

Participants were informed about the experiment procedure and fNIRS method, then they read and signed consent forms just before the experiment had started. The study was conducted in compliance with the WMA Declaration of Helsinki. Any payment wasn't made to the participants.

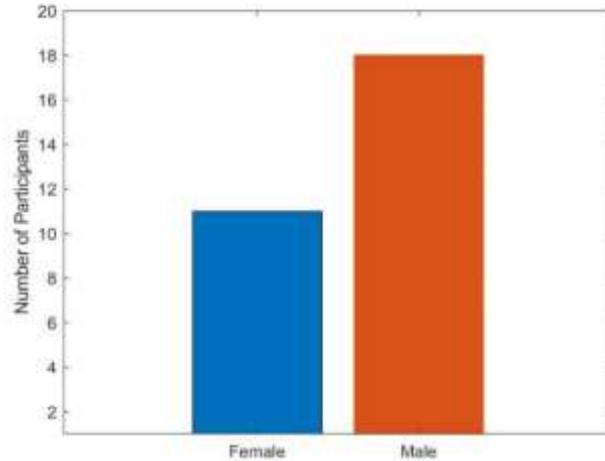


Figure 3.5: Number of participants by gender.

3.2.2. Audio-Visual Stimuli

Four audio-visual stimuli were used as experiment stimuli. Human face, robot face, human voice and robot voice stimuli were paired with Adobe Premiere® software and created two congruence and two incongruence face-voice stimuli pairs (Table 3.2).

Table 3.2: Audio-visual stimuli of the fNIRS experiment.

Audio-visual Stimuli	Congruency
Human Face-Human Voice	Congruent
Human Face-Robot Voice	Incongruent
Robot Face-Robot Voice	Congruent
Robot Face-Human Voice	Incongruent

Audio-visual videos of real human and primitive robot design were used as experiment stimuli. Real human stimulus was the same as 33 years old-male volunteer in previous behavioural experiment (Figure 3.6 a). Primitive robot design also was the same as unrealistic human stimuli in behavioural experiment (Figure 3.6 b). But this stimulus is named as robot face stimulus for fNIRS experiment. To underline contrast between real human and robot design; experiment stimuli mentioned as human face and robot face in the fNIRS results and discussion parts. 33 years old-male volunteer’s own voice was recorded and used as a human voice stimulus without any formatting. Robot voice stimulus was the same as the unrealistic voice in the previous behavioural experiment.

Both human and robot voice stimuli were consisted of “How are you, how is it going?” sentence like the previous experiment.

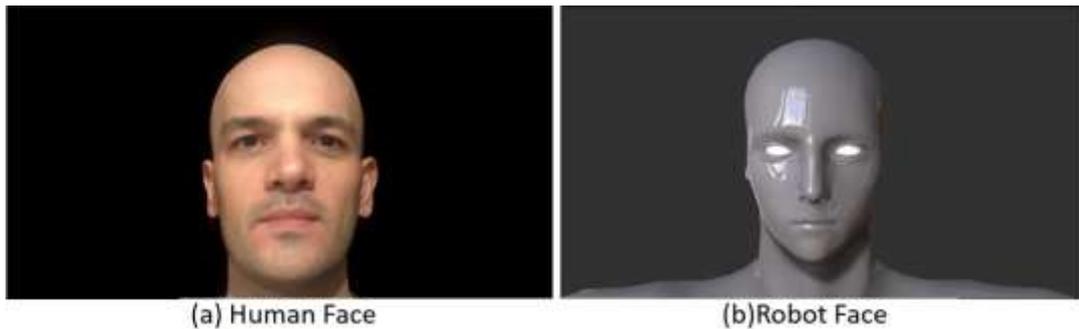


Figure 3.6: Sample static frames from the audio-visual stimuli.

3.2.3. Experimental Procedure

Audio-visual robot and human face videos were shown to participants in two episodes. In the first episode, they only watched stimuli videos from the screen while the fNIRS device was recording their PFC hemodynamic activity. Just after they had finished the first episode, they watched and rated the stimuli videos again.

Both episodes of the experiment were programmed with the open source PsychoPy3 software. Participants sat on a comfortable chair in front of a computer monitor which had a 60 Hz refresh rate, 3200x1800 resolution and 13 inches size. After instructions were given by the researcher, participants were alone in a silent dark room¹⁹⁸. They were asked to keep their eyes open and avoid head movements during the fNIRS recording episode. Potential feelings of discomfort due to the placement of the fNIRS optodes were checked before the onset of the experiment and it was assured that all participants had a comfortable experience (Figure 3.7).



Figure 3.7: fNIRS recording from a participant during watched experimental stimuli from the screen.

In the first fNIRS recording episode, 4 types of robot and human stimuli were presented, each of which lasted for 4 seconds, followed by a rest period of 13 seconds. A grey blank screen was presented during the rest periods. The order of stimuli was randomized and each type of stimuli was presented 10 times. Hence, the fNIRS recordings took approximately 12 minutes for each participant.

The second episode of the experiment consisted of a behavioural experiment. Self-assessment of uncanniness of robot and human stimuli by participants were rated by the participants with a 1 to 9-point scale where 1 point was for normal/neutral/trustful feelings and 9 points were given for the most uncanny/eerie/negative feelings. Turkish translations of these words about feelings (“Huzursuz”, “Normal”) were also placed on the rate screen. 4 robot and human stimuli were presented twice and rated by the participants. This episode took about 2 minutes (Figure 3.8).

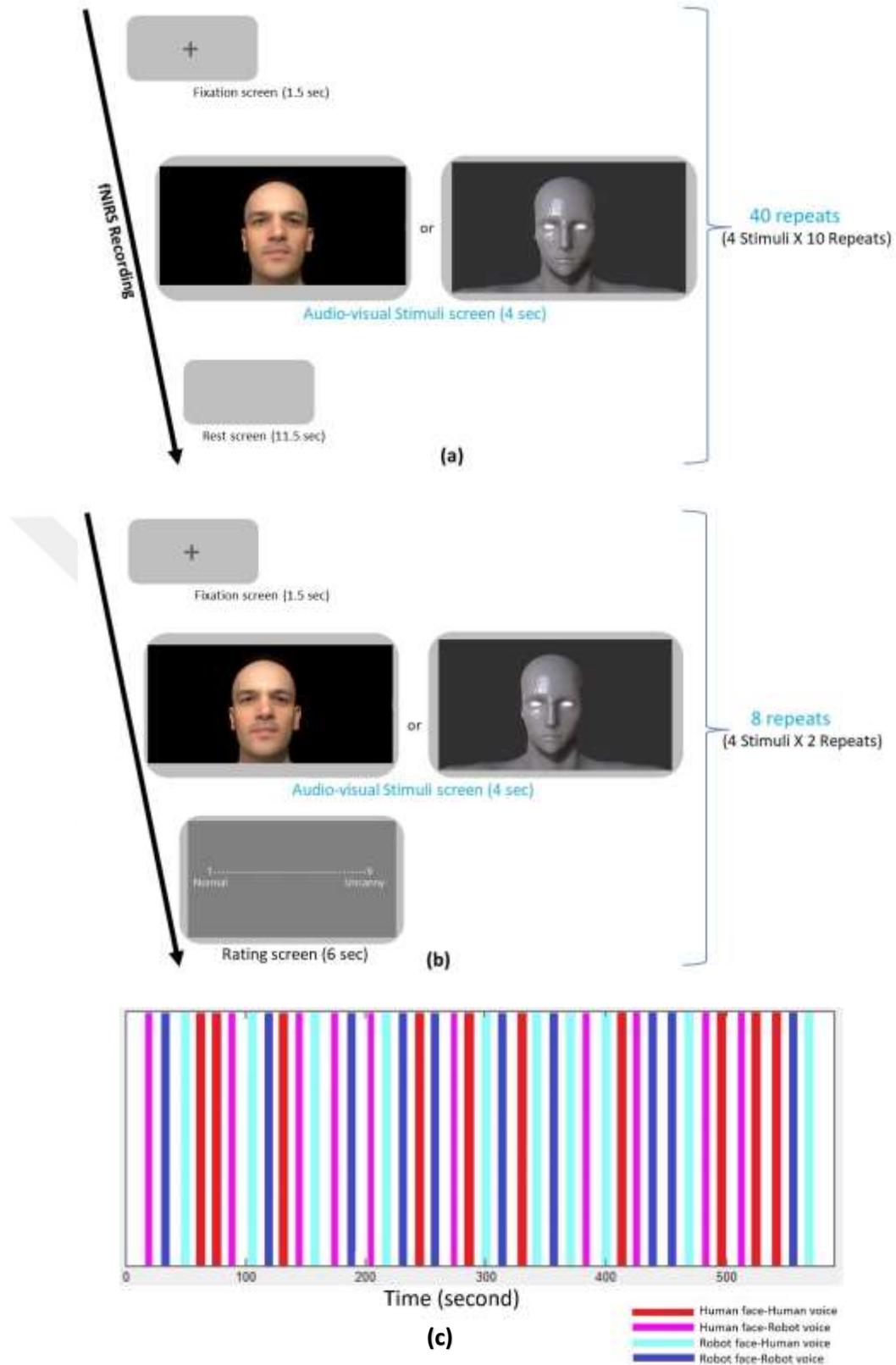


Figure 3.8: Experimental Design of neuroimaging experiment.
 (a) Experimental design of the fNIRS recording episode
 (b) Experimental design of the Behavioural episode
 (c) Randomized order of audio-visual stimuli at fNIRS recording episode. 4 stimuli repeat 10 times (4 x 10)

3.2.4. Data Analysis

3.2.4.1. Neuroimaging Experiment (First Episode)

-fNIRS Data Collection

A NIRSport functional near infrared spectroscopy system (NIRSport, NIRx Medical Technologies LLC, Berlin-Germany ²⁰¹) was used as a neuroimaging device to measure prefrontal cortical activation to emotional stimuli (Figure 3.5). The system involves 22 channels which consist of 8 light sources (emitting near-infrared light at 760 and 850 nm) and 7 detectors. The combinations of light source-detector pairs with a 3 cm distance are accepted as channels. All channels collect hemodynamic data from the frontal cortex area. Concentration changes of oxygenated hemoglobin and deoxygenated hemoglobin were calculated with the modified Beer-Lambert law ¹⁶⁴. The fNIRS signals had a 7.8125 Hz sampling frequency. Profile of probe sensitivity was calculated by the Atlas Viewer toolbox ²⁰² of Homer2 Software ²⁰³ to ensure that all channels collect data from the first few millimeters of the frontal cortex. With the AtlasViewer toolbox, each channel's photon propagation can be mapped to wavelength-specification.



Figure 3.9: NIRSport fNIRS device which is used in experiment.

-Data Pre-processing and Feature Selection

Data pre-processing of fNIRS signals involved several methods and steps. Initial visual inspection of data was performed with nirsLAB (NIRSport, NIRx Medical Technologies LLC, Berlin-Germany) ²⁰¹. Detailed analysis was carried out with HOMER2 scripts and customized MATLAB R2020B (Mathworks, Massachusetts-USA) scripts ^{204,205}.

Scripts of HOMER2 codes and functions formed the basis of our pre-processing pipeline. First, channels with poor signal quality were eliminated. Raw light intensity data were transformed to optical density (OD) data using HOMER2-hmrIntensity2OD.m function. Motion artifacts of the data were detected using HOMER2-hmrMotionArtifact.m function with the following parameters: Motion = 0.5, tMask = 1, STDEVthresh = 10, and AMPthresh = 1. Principal component analysis was also employed to remove motion artifacts with HOMER2-hmrMotionCorrectPCA.m function (nSV parameter=0.8). After motion correction steps, OD data were filtered with a butterworth bandpass filter which had a high frequency cut-off at 0.008 Hz and a low cut-off at 0.005 Hz. As the final data pre-processing step; oxy-Hb and deoxy-Hb concentrations of filtered OD data were calculated based on the Modified Beer-lambert law with HOMER2-hmrOD2Conc.m function ²⁰⁶.

Only oxy-Hb data were included in the data analysis since oxy-Hb is considered as a more reliable and well-grounded marker of cortical hemodynamic activation ^{207,208}. Hemodynamic signals from fNIRS recordings contain our signals of interest which are the neuronally induced hemodynamic changes but these neuronally induced effects are intermixed with cerebral and extracerebral physiological effects such as heart beat, respiration and Mayer waves. These systemic physiological effects may cause false negative and false positive activation patterns if they are not properly eliminated ²⁰⁹. Assuming that the systemic physiological activity is common across all channels, a principal component analysis was applied to whole channel data. Top principle components which explained 75 % of the covariance of all channel data were accepted as regressors modelling the common noise effect and they were linearly regressed out from time series of each channel separately ²¹⁰.

-fNIRS Data Analysis

Principal component analysis methods can be used to separate neural induced oxy-Hb signals from extracerebral and systemic physiological noise ²¹¹. Principal components of oxy-Hb signal data formed %75 covariance of all channel's signal. These principal components were accepted as regressors which represent extracerebral and physiological noise, so were excluded from each channel's oxy-Hb signal data.

For each channel's pre-processed oxy-Hb signal, 18-second-long block segments were which included each 4 sec single trial and spanned a 3 sec pre-stimulus baseline interval and an 11 sec post stimulus interval.

Each segment was detrended and classified into one of the four categories of the audio-visual stimuli trial types. The mean oxy-Hb signal for each condition was computed by averaging across time series of all trial blocks (n=10) belonging to each stimulus type. Block averaging procedure was performed for each subject and channel's oxy-Hb signal data separately. Hence, a single-block averaged time-series oxy-Hb signal data was calculated for each condition and channel for the subject. Customized hemodynamic effect size metric (Cohen's D) for every stimulus condition was computed by subtracting the mean of the signal in the [0-3] second pre-stimulus time range before the stimulus onset from the mean of the signal in the [1-4] second duration after the stimulus onset. Stimulus induced amplitude change with respect to the baseline was normalized by dividing the difference in amplitude with the standard deviation of the [1-3] second pre-stimulus baseline in the light of known procedure ^{212,213} (Figure 3.10).

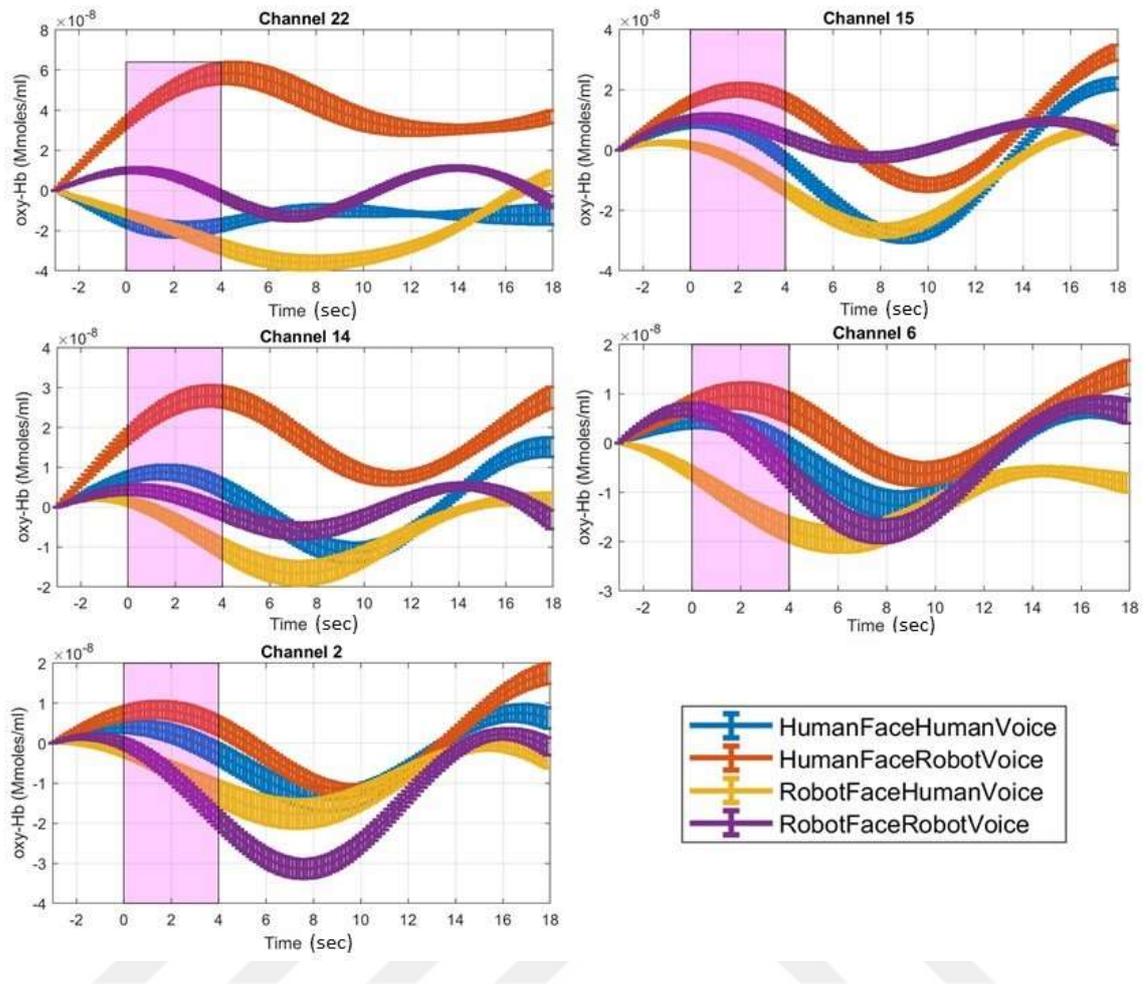


Figure 3.10: Pre-processed $\Delta[\text{deoxy-Hb}]$ time series graphic of each audio-visual stimuli in significant channels. $\Delta[\text{oxy-Hb}]$ is calculated with concentration change of oxyhemoglobin (oxy-Hb) in micromoles at probed brain tissue. Each time track indicates block average of oxyhemoglobin responses detected during each specific audio-visual stimulus from the same channel of all participants. Pink shaded areas represent audio-visual stimulus intervals. Error bars indicate the standard error value across participants.

-Statistical Analysis of Hemodynamic Signal Data

A 2x2 repeated measures mixed ANOVA (face: human, robot; voice: human, robot) analysis was employed on Cohen's D metric of each channel separately to localize statistically significant differences in hemodynamic signal activation at the group level across different stimuli types. Post-hoc analyses were performed with ANOVA analysis corrected with a Bonferroni procedure. Pearson's correlation between Cohen's D metrics and all participant's behavioural rating scores were calculated and illustrated in scatter plots. All statistical analyses were executed with JASP ²⁰⁰.

3.2.4.2. Behavioural Experiment (Second Episode)

30 participants scored audio-visual human and robot videos between normal and uncanny emotions. Average uncanniness scores for each of the 4 audio-visual stimuli were calculated. A 2x2 (Face (Human, Robot) x Voice (Human, Robot)) repeated measures ANOVA were applied for detailed analysis of each stimuli's uncanniness score.



4. RESULTS

4.1. Behavioural Experiment

4.1.1. Multivariate ANOVA Analyses on Unimodal and Multimodal Stimuli

6 unimodal stimuli of the experiment were analysed with Multivariate ANOVA. One only visual stimulus and one only auditory stimulus was rated significantly different by age groups. Only realistic face stimuli was rated significantly more uncanny by the older age group than younger ($M=3.55$, $S.E.=0.43$; $F(1,58)=6.42$, $p=0.014$). Only semi-realistic voice stimuli were rated significantly more uncanny by younger age groups than older ($M=5.37$, $S.E.=0.37$; $F(1,58)=9.63$, $p=0.003$) (Figure 4.1).

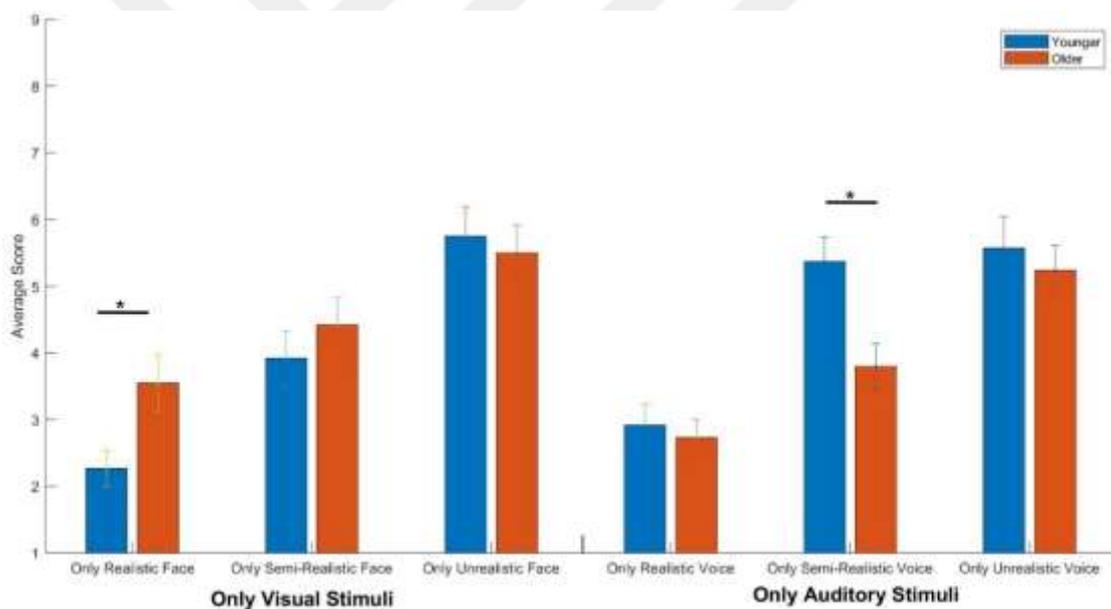


Figure 4.1: Average uncanniness scores of Unimodal stimuli by age group.

10 multimodal audio-visual stimuli of experiment were analysed with Multivariate ANOVA. One audio-visual stimulus was rated significantly different by age groups. Realistic face-realistic voice stimuli was rated significantly more uncanny by the older age group than younger ($M=3.68$, $S.E.=0.38$; $F(1,58)=7.35$, $p=0.009$) (Figure 4.2).

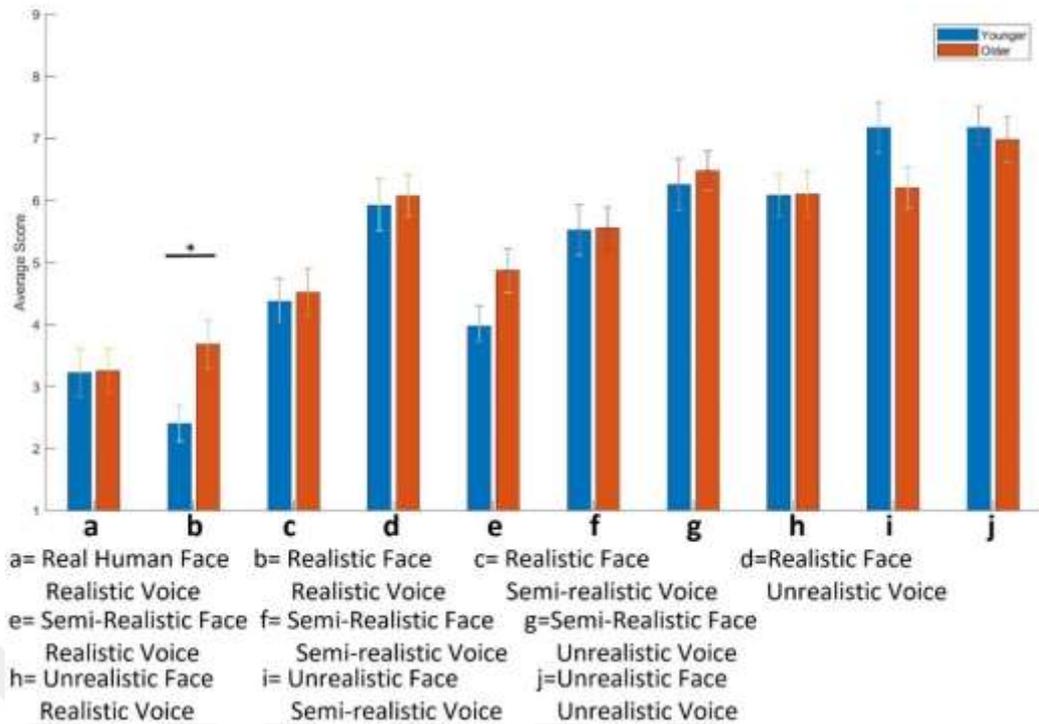


Figure 4.2: Average uncanniness scores of Multimodal stimuli by age group.

4.1.2. Repeated Measures ANOVA Analyses

4.1.2.1. Unimodal Stimuli: Only Visual and Only Auditory Conditions

Visual: A 2 (Age: Old, Young) x 3 (Naturalness: Realistic, Semi-realistic, Unrealistic) mixed ANOVA on the ratings given for the visual stimuli showed a main effect of naturalness ($F(2,116)=48.75$, $p<0.001$, $\eta^2_p = 0.46$). Unrealistic faces elicited significantly higher uncanny scores than semi-realistic faces ($t=5.30$, $p<0.001$) and realistic faces ($t=9.87$, $p<0.001$). Also, semi-realistic faces elicited significantly higher uncanny scores than realistic faces ($t=4.57$, $p<0.001$).

There was also an interaction between age and naturalness ($F(2,116)=3.88$, $p=0.023$, $\eta^2=0.063$). In the young group, the unrealistic face elicited significantly higher uncanny scores than the realistic face ($t=4.71$, $p<0.001$) whereas in the old group there was no significant difference between the two ($t=2.78$, $p=0.095$). Similarly, in the young group, the semi-realistic face elicited significantly higher uncanny scores than the realistic face ($t=4.24$, $p<0.001$) whereas no such difference was found between the two in the old group ($t=2.23$, $p =0.42$). There was no effect of age on the uncanny ratings ($F(1,58)=1.19$, $p=0.28$). Bonferroni corrections were done for all multiple comparisons (Figure 4.3 a).

Auditory: A 2 (Age: Old, Young) x 3 (Naturalness: Real, Semi-realistic, Unrealistic) mixed ANOVA on the ratings given for the auditory stimuli also showed a main effect of naturalness ($F(2,116)=49.42$, $p<0.001$, $\eta^2p=0.46$). Unrealistic voices elicited significantly higher uncanny scores than semi-realistic voices ($t=-3.10$, $p=0.007$) and realistic voices ($t=-9.73$, $p<0.001$). Also, semi-realistic voices elicited significantly higher uncanny scores than realistic voices ($t=-6.63$, $p<0.001$).

There was also an interaction between age and naturalness ($F(2,116)=4.12$, $p=0.019$, $\eta^2p=0.066$). The semi-realistic voice elicited significantly higher uncanny scores than the realistic voice in the young group ($t=-6.53$, $p<0.001$) but not in the old group ($t=-2.85$, $p=0.079$). In addition, the unrealistic voice elicited significantly higher uncanny scores than the semi-realistic voice in the old group ($t=-3.85$, $p=0.003$) but not in the young group ($t=-0.53$, $p=1.0$). There was no effect of age on the uncanny ratings ($F(1,58)=2.83$, $p=0.098$). Bonferroni corrections were done for all multiple comparisons (Figure 4.3 b).

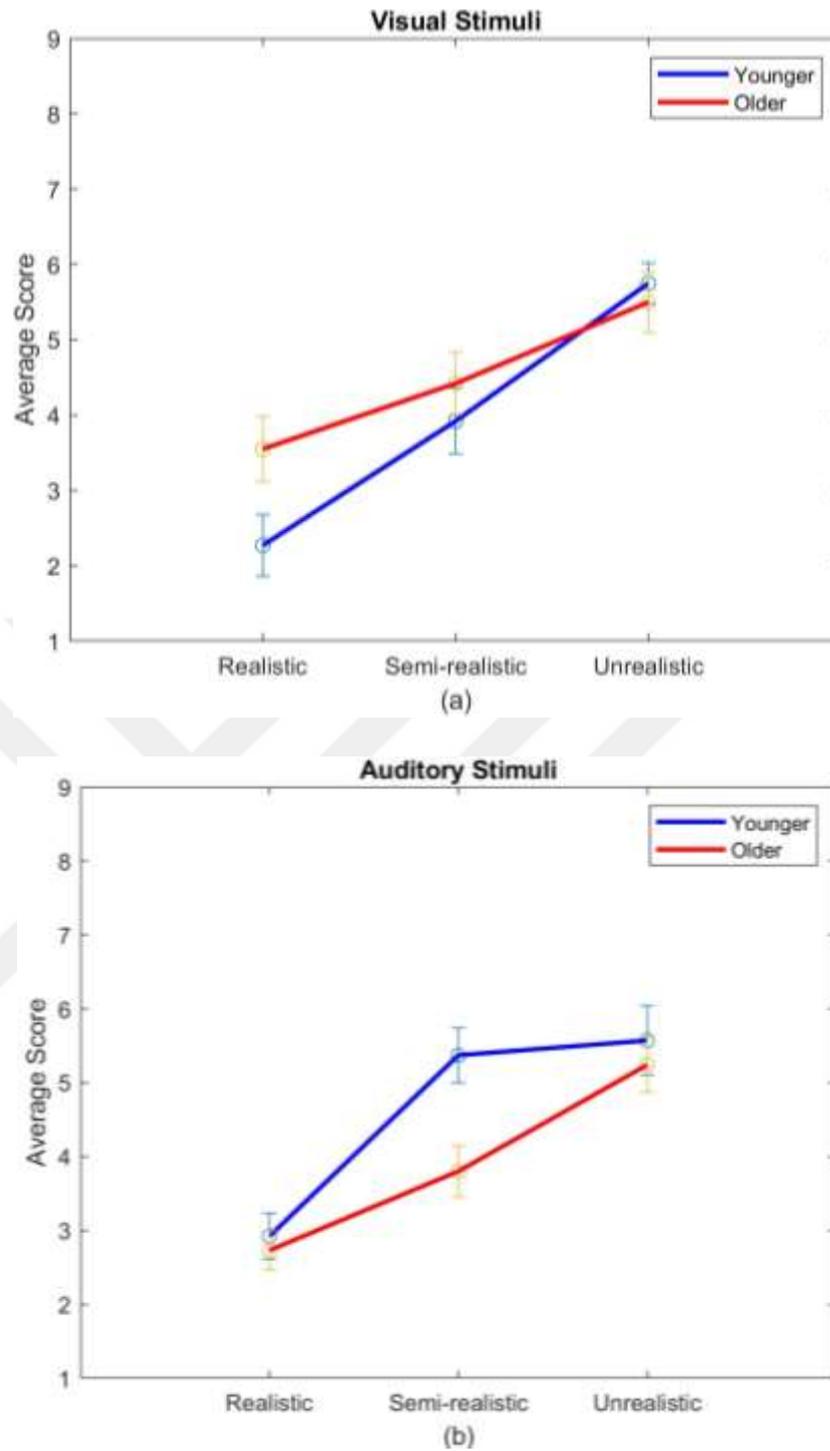


Figure 4.3: Average uncanniness scores of the unimodal stimuli across age groups. (a) Visual stimuli, (b) Auditory stimuli.

4.1.2.2. Multimodal Stimuli: Audio-visual conditions

A 2 (Age: Old, Young) x 3 (Visual modality: Realistic, Semi-realistic, Unrealistic) x 3 (Auditory modality: Realistic, Semi-realistic, Unrealistic) mixed ANOVA on the ratings of the audio-visual stimuli showed a main effect of visual modality ($F(2,116)=71.91$, $p<0.001$, $\eta^2p=0.45$) and a main effect of auditory modality ($F(2,116)=47.86$, $p<0.001$, $\eta^2p=0.55$).

Multimodal stimuli that featured unrealistic faces elicited higher uncanny scores than the ones that featured semi-realistic faces ($t=-6.634$, $p<0.001$) and realistic faces ($t=-11.97$, $p<0.001$). Also, multimodal stimuli that featured semi-realistic faces elicited higher uncanny scores than the ones that featured realistic faces ($t=-5.34$, $p<0.001$).

Multimodal stimuli that featured unrealistic voices elicited higher uncanny scores than the ones that featured semi-realistic voices ($t=-4.61$, $p<0.001$) and realistic voices ($t=-9.78$, $p<0.001$). Also, multimodal stimuli that featured semi-realistic voices elicited higher uncanny scores than the ones that featured realistic voices ($t=-5.17$, $p<0.001$).

There was also an interaction between age and visual modality ($F(2,116)=3.77$, $p=0.026$, $\eta^2p=0.061$), age and auditory modality ($F(2,116)=3.19$, $p=0.045$, $\eta^2p=0.052$), and visual modality and auditory modality ($F(4,232)=23.38$, $p<0.001$, $\eta^2p=0.287$).

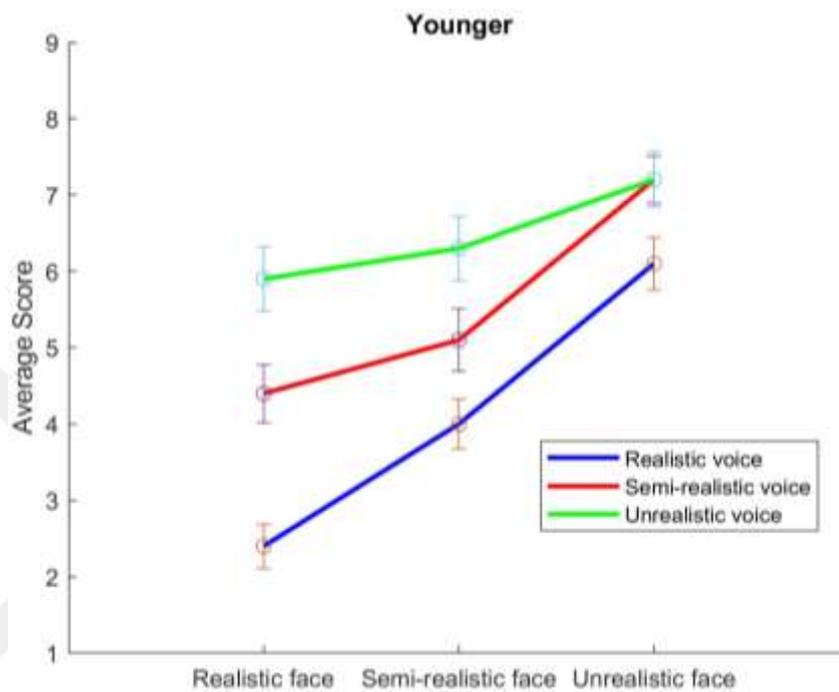
In both young and old group, visual stimuli that featured unrealistic faces elicited higher uncanny scores than the visual featured semi-realistic faces (young:($t=-6.21$, $p<0.001$), old:($t=-2.68$, $p=0.125$)) and realistic faces (young:($t=-10.27$, $p<0.001$), old:($t=-4.05$, $p=0.001$)). Also, visual stimuli that featured semi-realistic faces elicited higher uncanny scores than the realistic faces (young:($t=-5.04$, $p=0.001$), old:($t=-3.49$, $p=0.01$)) in both age groups.

In both age groups, auditory stimuli that featured unrealistic voices elicited significantly higher uncanny scores than the auditory featured realistic voices (young:($t=-8.09$, $p<0.001$), old:($t=-5.73$, $p<0.001$)). Also, auditory featured semi-realistic voices elicited significantly higher uncanny scores than realistic voices ($t=-5.4$, $p<0.001$) in the young group but not in the old group ($t=-1.9$, $p=0.89$). In old group, auditory stimuli that featured unrealistic voices elicited significantly higher uncanny scores than the auditory featured semi-realistic voices ($t=-3.83$, $p=0.003$) but there wasn't significant difference with same comparison in young ($t=-2.68$, $p=0.125$).

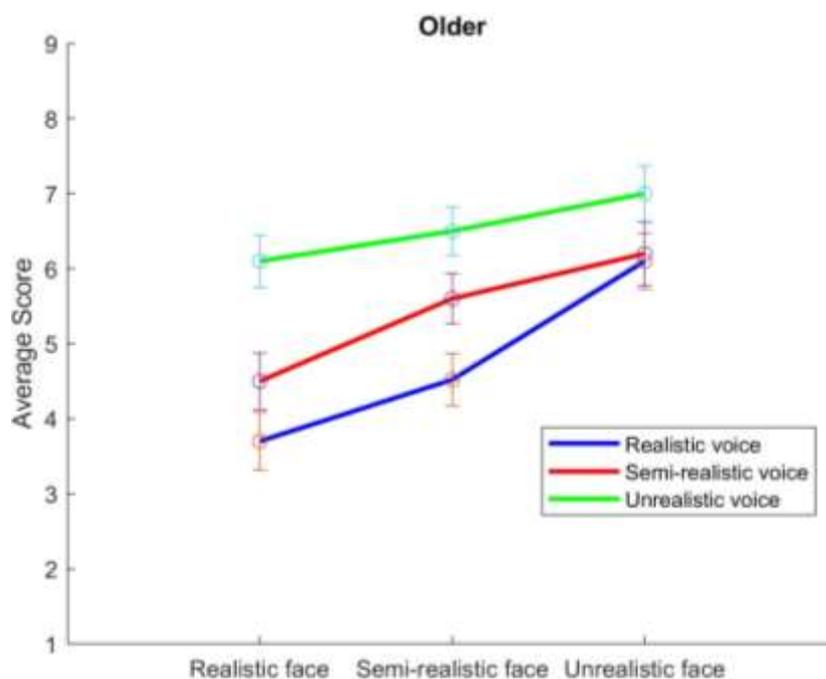
Multimodal unrealistic face-unrealistic voice stimuli elicited significantly higher uncanny scores than most stimuli ($p=0.038$ with semi-realistic face-unrealistic voice

stimuli, $p=0,001$ with unrealistic face-realistic voice stimuli, others $p<0.001$). But unrealistic face-semi-realistic voice stimuli didn't have a significant difference with unrealistic face-unrealistic voice stimuli ($t=-1.68$, $p=1$). Realistic face-realistic voice stimuli elicited significantly lower uncanny scores than other multimodal stimuli (all $p<0.001$). Bonferroni corrections were done for all multiple comparisons (Figure 4.4).

There was no effect of age ($F(1,58)=0.21$, $p=0.646$).



(a)



(b)

Figure 4.4: Average uncanniness scores of audio-visual stimuli across age groups. (a) Younger, (b) Older

4.1.2.3. Congruency Situation and Age Group Comparison

A 2 (Age: Old, Young) x 2 (Congruency: Congruence, Incongruence) mixed ANOVA on the ratings of the congruency situation of audio-visual stimuli pairs showed a strong main effect of congruency ($F(1,29)=27.01$, $p<0.001$, $\eta^2p=0.48$). There was also an interaction between age and congruency ($F(1,29)=5.53$, $p=0.026$, $\eta^2p=0.16$).

For the young age group, incongruent stimuli pairs elicited significantly higher uncanny scores than congruent stimuli pairs ($t=-5.58$, $p<0.001$). At the old age group, incongruent stimuli pairs elicited significantly higher uncanny scores than congruent stimuli pairs ($t=-2.8$, $p=0.042$). However, the difference between congruent and incongruent stimuli were more pronounced in the younger group compared to the older group. Bonferroni corrections were done for all multiple comparisons (Figure 4.5).

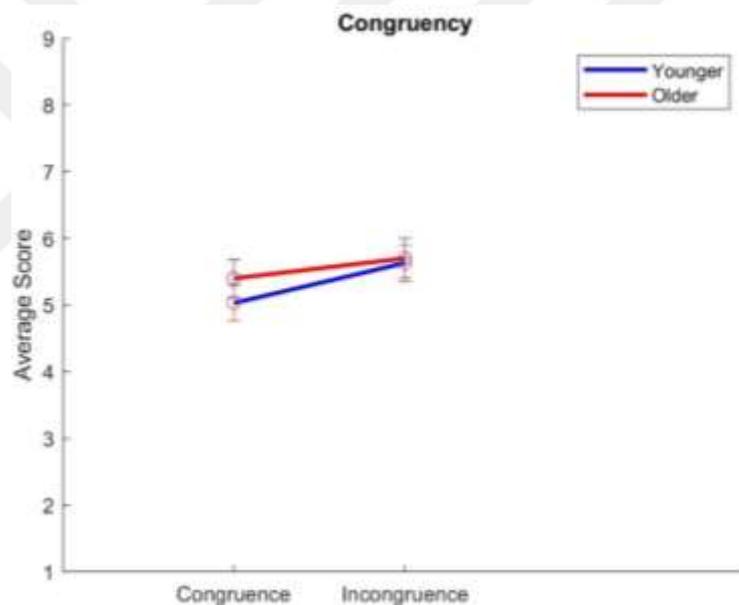


Figure 4.5: Average uncanniness scores of Congruency situation between age groups.

4.1.2.4. Unimodal and Multimodal Stimuli Together

An omnibus 2 (Age: Old, Young) x 3 (Modality: Only Visual, Only Auditory, Audio-visual) x 3 (Naturalness: Realistic, Semi-realistic, Unrealistic) mixed ANOVA showed a main effect of modality ($F(2,116)=25.73$, $p<0.001$, $\eta^2p=0.31$). Multimodal stimuli elicited higher uncanny scores than the unimodal stimuli (for visual: $t=-6.30$, $p<0.001$; for auditory: $t=-6.12$, $p<0.001$). There was no significant difference in the scores of the only visual and only auditory stimuli ($t=-0.19$, $p=1.0$).

There was also a main effect of naturalness ($F(2,116)=110.37$, $p<0.001$, $\eta^2p=0.66$). Unrealistic stimuli elicited higher uncanny scores than the semi-realistic ($t=-6.92$, $p<0.001$) and realistic stimuli ($t=-14.85$, $p<0.001$). In addition, semi-realistic stimuli elicited higher uncanny scores than the realistic stimuli ($t=-7.93$, $p<0.001$). There was no effect of age ($F(1,58)=1.22 \times 10^{-7}$, $p=1.0$).

There was also an interaction between age and naturalness ($F(2,116)=4.02$, $p=0.021$, $\eta^2p=0.065$), age and modality ($F(2,116)=4.66$, $p=0.011$, $\eta^2p=0.074$), and age, modality, and naturalness ($F(4,232)=3.90$, $p=0.004$, $\eta^2p=0.043$). The interaction between modality and naturalness was marginally significant ($F(4,232)=2.58$, $p=0.051$, $\eta^2p=0.043$). Multimodal stimuli elicited higher uncanny scores than the auditory stimuli for the realistic and unrealistic conditions (all $p<0.001$) but not for the semi-realistic condition ($t=-3.17$, $p=0.061$). In addition, multimodal stimuli elicited higher scores than the auditory stimuli for the old group but not for the young group ($t=-2.81$, $p=0.087$) (Figure 4.6).

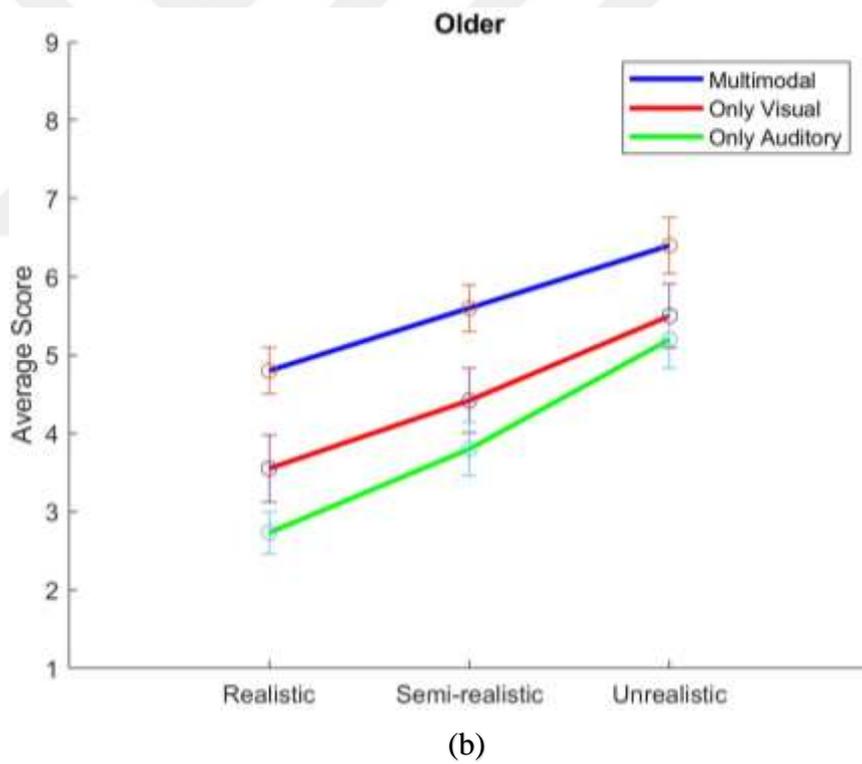
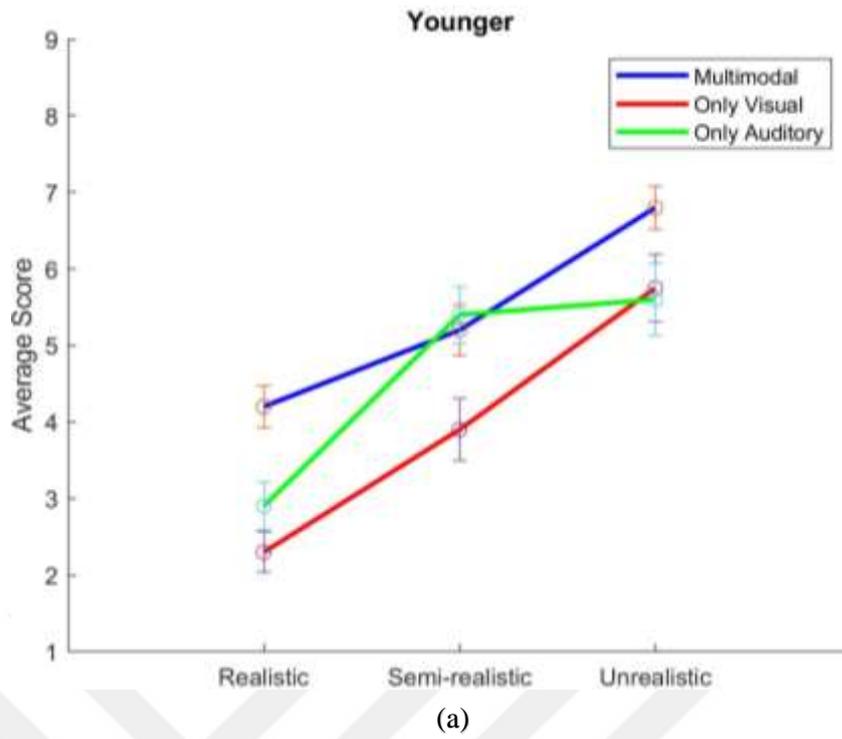


Figure 4.6: Average uncanniness scores across all modality types and age groups. (a) Younger, (b) Older

4.2. Neuroimaging Experiment

4.2.1. Repeated Measures ANOVA Analysis on Cohen's D Metric

Differences in Cohen's D metric of all subjects across different trial types were statistically analysed with a 2 x 2 ANOVA design for each channel separately. A main effect of face was observed in Channels 6,14, 22, a main effect of voice was observed in Channel 15 and an interaction effect was observed in Channel 2.

The 2 channels in the left DLPFC area of PFC (Channel 6, Channel 14), 1 channel in the right DLPFC area (Channel 2) and 2 channels in the OFC area (Channel 15, Channel 22) were elicited significant hemodynamic activity changes between human and robot, face and voice stimuli are illustrated in Figure 4.7.

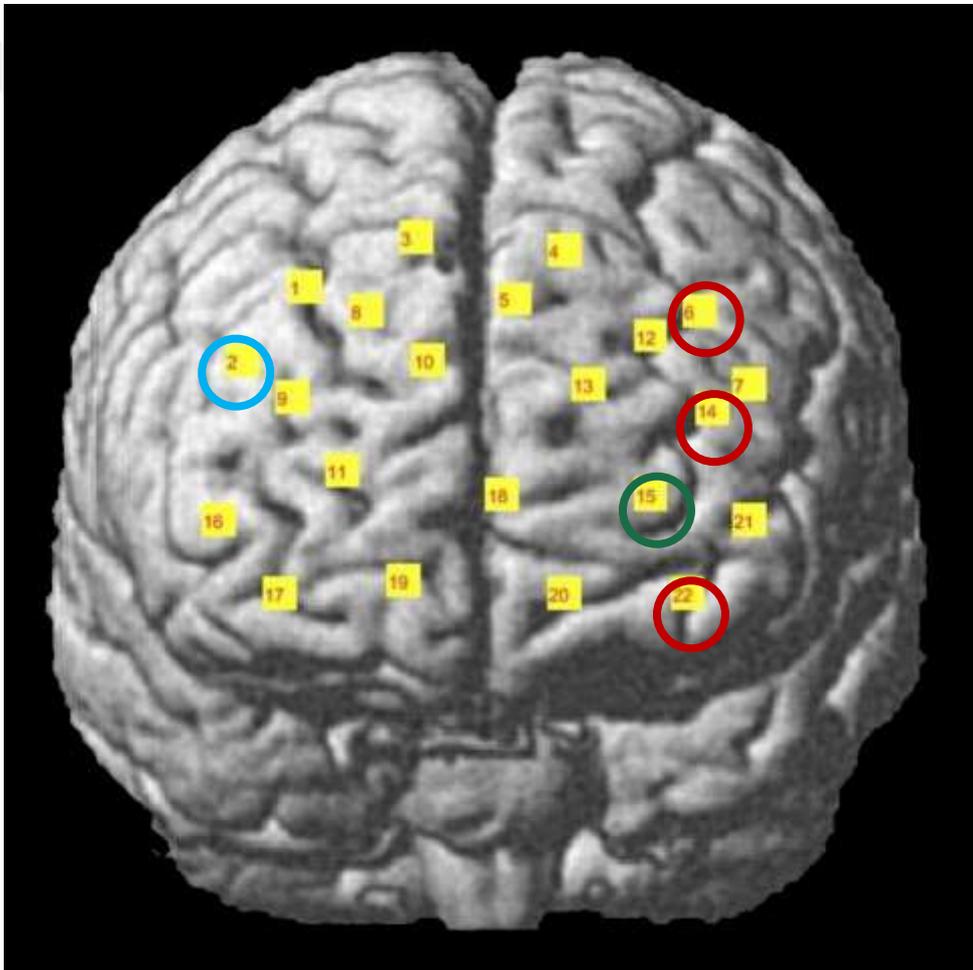


Figure 4.7: Channel locations of fNIRS probe mapped onto a standard brain template in MNI space. Channels with significant hemodynamic activation are illustrated with colored circles.

(O: Human Face> Robot Face O: Robot Voice> Human Voice(deactivation)

O: Human Face Robot Voice>Robot Face Robot Voice).

A 2 (face: human, robot) x 2 (voice: human, robot) mixed ANOVA analyses were applied to all 22 channels to calculate hemodynamic activity changes with different face and voice stimuli at Cohen's D metric.

At Channel 6, Channel 14 and Channel 22, significantly higher hemodynamic response to the main effect of human face stimuli than robot face stimuli were detected (for Channel 6 $t=2.7$, $p=0.012$, for Channel 14 $t=2.05$, $p=0.05$, for Channel 22 $t=2.69$, $p=0.012$) (Figure 4.8 A).

At Channel 15, significantly lower hemodynamic response (hemodynamic deactivation) to the main effect of robot voice than human voice was detected ($t=-2.37$, $p=0.025$) (Figure 4.8 B).

At Channel 2, interaction effect was observed. Significantly higher hemodynamic responses to human face-robot voice stimuli than robot face robot-voice stimuli were detected ($t=2.87$, $p=0.045$) (Figure 4.8 C).

Bonferroni corrections were applied in all analyses at post-hoc tests (Table 4.1).

Table 4.1: Post-hoc comparisons of Cohen's D metric of hemodynamic response to different stimuli at represented channels.

Channel	Stimuli		Mean Difference(CI:%95)	t	P value
6	Human Face	Robot Face	3.42	2.7	0.012
14	Human Face	Robot Face	2.1	2.05	0.05
22	Human Face	Robot Face	3.27	2.69	0.012
15	Human Voice	Robot Voice	-2.72	-2.37	0.025
2	Human Face Robot Voice	Robot Face Robot Voice	7.49	2.78	0.045

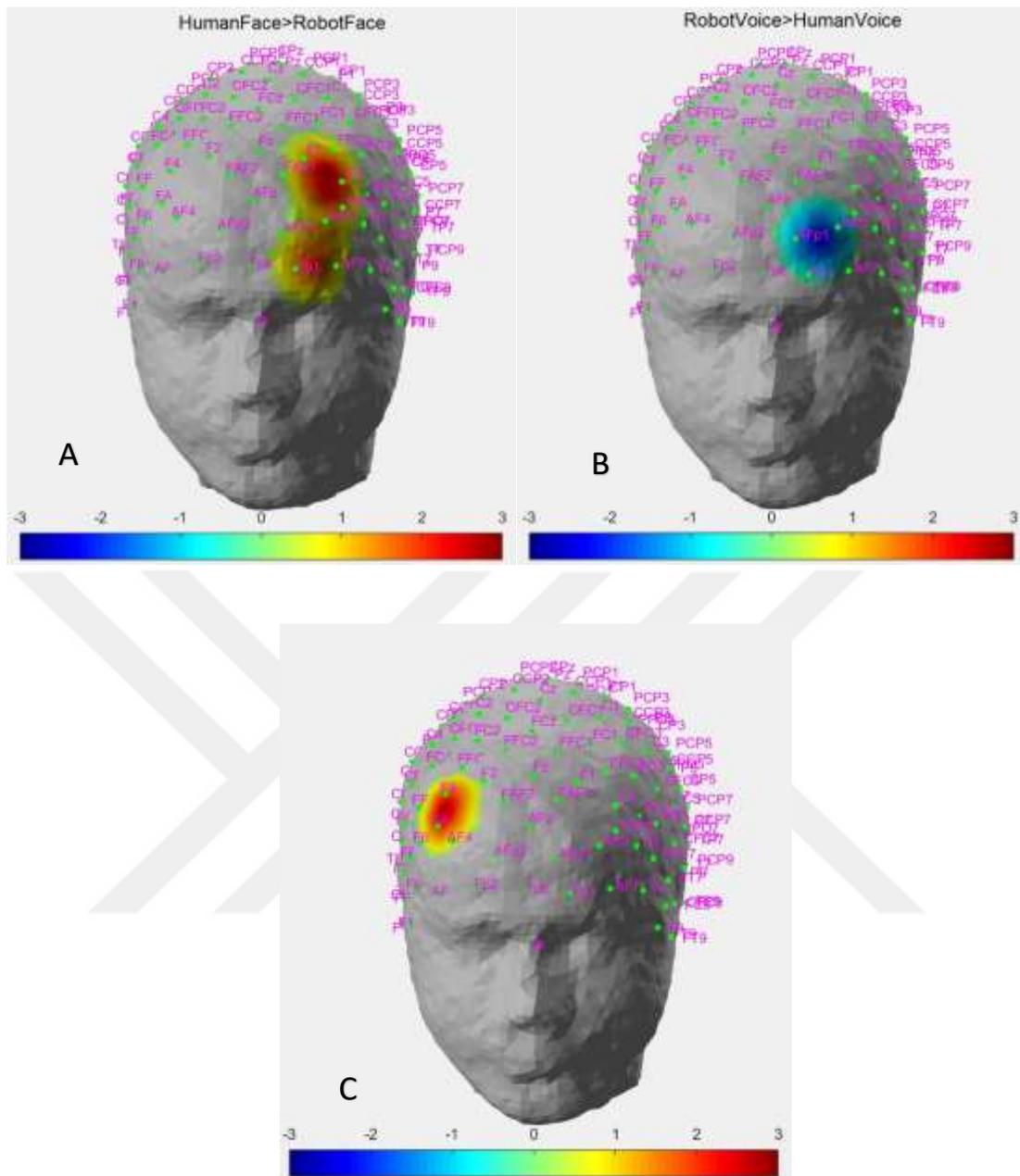


Figure 4.8: Hemodynamic activation maps of main effect and interactions of audio-visual stimuli. (A) Main effect of face: Human Face > Robot Face contrast, (B) Main effect of voice: Robot Voice > Human Voice contrast, (C) Face-voice interaction: Human Face Robot Voice > Robot Face Robot Voice contrast. T scores of channels showing statistically significant activation ($p < 0.05$) are mapped on to the standard head model map. Color bar represents threshold t statistic scores.

4.2.2. Correlation Analysis between Hemodynamic and Behavioural Data

Pearson's correlation coefficients were computed between behavioural ratings of the stimuli and Cohen's D metric of significantly active channels. At Channel 22, significant moderate correlation between behavioural ratings and Cohen's D hemodynamic activity metric was detected for the Human Face Robot Voice>Robot Face Robot Voice contrast ($R=0.431$, $n=24$ and $p<0.05$) (Figure 4.9).

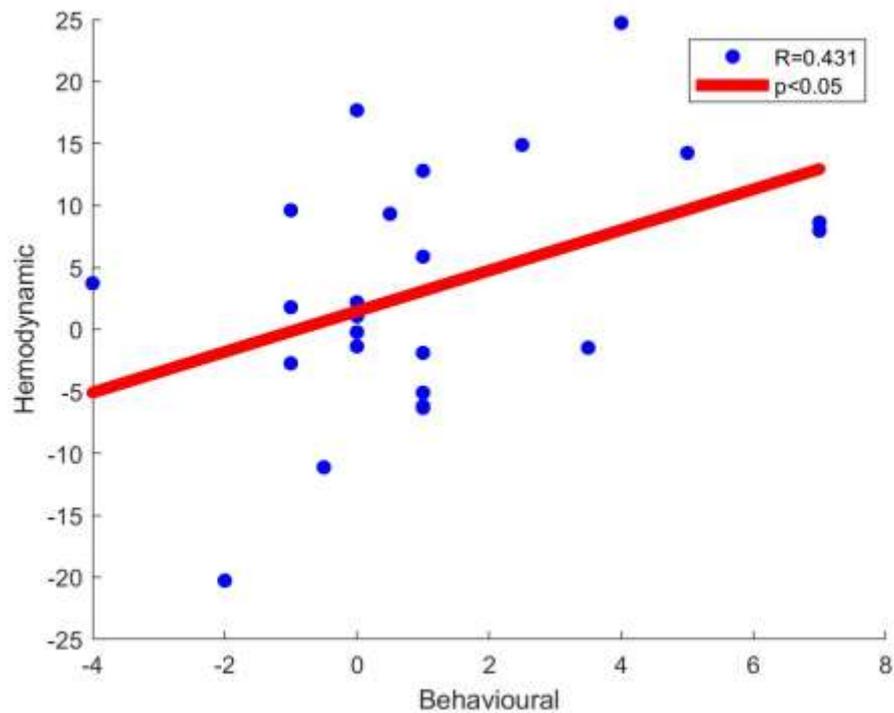


Figure 4.9: Scatter plots of behavioural data (Uncanniness Rating) and Cohen's D metrics computed for Human Face Robot Voice> Robot Face Robot Voice contrast. Each dot represents a comparison of changes in behavioural score and hemodynamic parameter of channel 22 for each subject.

4.2.3. Results of the Behavioural Episode

Average uncanniness scores of all stimuli are listed in Table 3.3.

Table 4.2: Average uncanniness scores of audio-visual stimuli.

Stimuli Type	Average Score
Human Face-Human Voice	3.61±0.45
Human Face-Robot Voice	6.1±0.41
Robot Face-Human Voice	4.8±0.44
Robot Face-Robot Voice	5.1±0.44

A 2 (face: human, robot) x 2 (voice: human, robot) mixed ANOVA design performed on the ratings given for each stimuli showed a strong main effect of voice ($F(1,29)=15.5, p<0.001, \eta^2p=0.35$). There was also an interaction between face and voice stimuli ($F(1,29)=8.47, p=0.007, \eta^2p=0.23$).

Human face-robot voice stimuli elicited significantly higher uncanny scores than the Human face-human voice stimuli ($t=-4.84, p<0.001$). Robot face-robot voice stimuli also elicited significantly higher uncanny scores than the Human face-human voice stimuli ($t=-3.13, p<0.017$).

Bonferroni corrections were applied for the analysis (Figure 4.10).

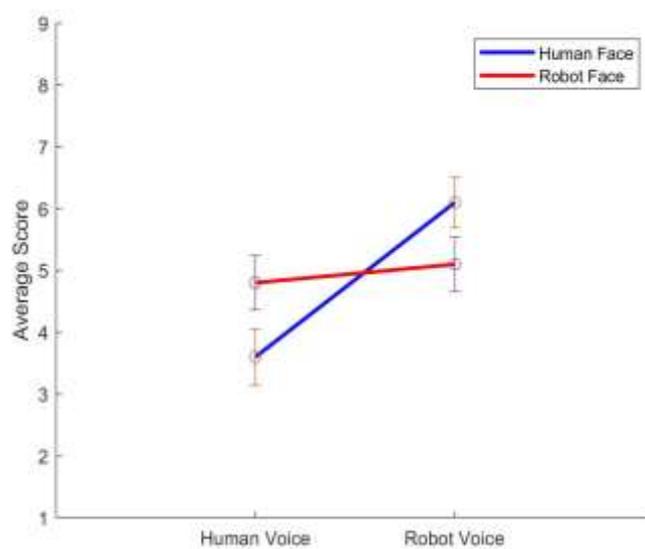


Figure 4.10: Average uncanniness scores of audio-visual stimuli.

5. DISCUSSION AND CONCLUSION

5.1. Discussion of the Behavioural Experiment

5.1.1. Scope of the Behavioural Experiment

We conducted a behavioural experiment to explore the uncanniness caused by audio-visual components of face and voice stimuli that represent different levels of human-robot attributes. Previous research shows that humans reportedly have more positive feelings and trust in human-like agents than mechanical robotic agents and prefer human-like faces and voices for interaction^{214,215}. We hypothesized that dissonant auditory and visual stimuli pairs could violate our conceptual expectation of humans and different types of robots.

Human faces and voices were evaluated in three different naturalness levels. Custom made unrealistic, semi-realistic and realistic face and voice designs were used as experimental stimuli. We investigated how multimodal stimuli and the congruence of visual and auditory aspects of the stimuli contribute to the uncanniness perception and differ from the auditory and visual components.

5.1.2. Naturalness

Robotic featured face and voice designs in our experiment caused a high level of eeriness/uncanny ratings compared to the human-like designs. As expected, control stimulus (real face-realistic voice) was rated with normal and lower uncanniness feelings. Multimodal realistic face-voice paired stimuli scored with the lowest uncanniness and unrealistic face-voice paired stimuli scored with the highest uncanniness. These polarized results meet our expectation that people tend to have normal and positive feelings towards humanistic figures than unnatural mechanical figures, which can be considered as a validation of our stimulus.

There was a trend of interaction between voice and face aspects, which could be a potential support for how different voices are evaluated particularly for different faces and the other way around. There is a linear trend from normal scores to uncanny scores between realistic, semi-realistic and unrealistic audio-visual stimuli. Realistic voice based multimodal stimuli have lower uncanniness than semi-realistic and unrealistic voice-based stimuli. We observed a bigger score gap between realistic voice paired, semi-

realistic voice paired stimuli than semi-realistic voice paired, unrealistic voice paired stimuli. Thus, we can say that realistic voice stimuli have a dominant role on normal feelings in audio-visual stimuli comparison.

5.1.3. Unimodal Stimuli

Unimodal visual stimuli had a significant effect on uncanniness score especially in young participants. Unrealistic faces elicited higher uncanniness than semi-realistic faces and semi-realistic faces elicited higher uncanniness than realistic faces significantly in the young age group. However older participants didn't react significantly to realistic and unrealistic faces. Young people's high exposure to human and robot designs and familiarity may have caused layered responses to different realism levels of visual stimuli²¹⁶. Uncanniness score differences between realistic and unrealistic visual designs were less in the older group. Older people's preference over realistic faces may have resulted with higher uncanniness and high acceptance threshold to graphical designs of humans, so elderly had a smoother reaction to different realism levels of visual stimuli.

Unimodal auditory stimuli had distinct responses from older and younger age groups. Younger group reacted with a significantly higher uncanniness score to semi-realistic faces than realistic faces; but the older group reacted with a significantly higher uncanniness score to unrealistic faces than semi-realistic faces. These results reveal younger people's distinctive reactions on realistic voice stimuli which occurred similarly on realistic face stimuli.

5.1.4. Multimodal Stimuli

Multimodal features of both auditory and visual stimuli had a significant main effect on uncanniness score, validation of different naturalness levels of auditory and visual stimuli had distinct reactions from participants. Multimodal featured visual stimuli had significantly different reactions with all realism levels in both age groups, in which unrealistic faces elicited higher uncanniness than semi-realistic faces and semi-realistic faces elicited higher uncanniness than realistic faces. However, multimodal featured auditory stimuli significantly elicited higher uncanniness scores on unrealistic voices than realistic voices in both age groups, other semi-realistic and unrealistic comparisons did not have consistent levelled responses in older nor in younger. Dissimilar responses independent from age to all realism levels may indicate that visual stimuli have a more

dominant effect on uncanniness scores than auditory stimuli in multimodal conditions. While our results support that the visual component is the determinant factor of uncanny valley effect but the auditory component is also a nearly determinant component ²¹⁷.

5.1.5. Age Effect on Uncanny Valley

We obtained promising results from generation-based comparisons in our experiment. Both the older and younger age groups scored realistic face paired stimuli with the lowest uncanniness, but significant differences were found in multimodal and unimodal realistic stimuli between generations. Younger age group scored multimodal realistic face-realistic voice stimuli with the lowest uncanniness, but the older age group scored control stimulus (real face-realistic voice) with the lowest uncanniness. In addition, the younger age group scored multimodal realistic face-realistic voice stimuli and unimodal only realistic face stimuli significantly lower uncanniness than the older age group.

It can be assumed that the younger generation is less sensitive and more familiar with animated and design faces of humans, but the older generation strongly prefers real human conditions rather than designs. The younger generation is exposed to a lot of graphic human design from video games and animated movies from their childhood, but graphic human designs is a relatively new concept for older people ²¹⁸. Beyond this; older age group reacted to unimodal and multimodal stimuli with linear uncanniness from realistic to unrealistic. But the younger age group broke the linear trend and scored realistic, semi-realistic and unrealistic stimuli separately, and modality had effects on scores. Younger population can interact with robots responsively and has layered perception to robots, but older people have tended to generalize robot concepts and neglect robotic attitudes ²¹⁹. This assumption can be supported with elder's inclusive preference on human-like robots, regardless of their function ²²⁰.

Older participants have distinct uncanniness scores on realist face-unrealistic voice stimulus than realistic face-voice stimulus. Negative feelings on incongruence stimuli suggest that mismatch between face-voice designs can cause uncanny emotions in older generations. In previous studies, older people report negative and uncanny feelings during the human-robot interaction processes ²²¹. Our results suggest that the conceptual congruence could be the main effect for the uncanny valley in the older population. Regarding this result, it is also important to note that different exposures of

young and old populations to technological developments may cause them to develop different concepts about robot perception and human-robot interaction.

5.1.6. Limitations and Future Works

Present behavioural study has some limitations. First; we used only visual, auditory and audio-visual face and voice videos as experimental stimuli. Uncanniness score means behavioural responses to experimental stimuli and we only can predict subjective feelings of participants from this score. To evaluate objective outcomes of uncanny feelings from participants, neuroimaging methods should be included in experimental settings. At behavioural experiment dimension, our suggestions are limited with increased or decreased levels of uncanny feelings, but neuroimaging methods allows specifying certain brain regions to experimental stimuli.

Second; unimodal and multimodal videos of experimental stimuli create auditory and visual perception sources. Behavioural experiments with real human and physical robot stimuli have rich cognitive outcomes and more layered perception sources. In addition to present auditory and visual; haptic perception tasks can be executed with real human and physical robot stimuli.

5.1.7. Conclusion

We find that particular auditory or visual aspects tend to dominate the uncanniness perception of an animated robot-like design. Auditory components are a determinant factor at uncanny valley effect as well-known visual components. Multimodal audio-visual stimuli create distinct uncanny feelings than unimodal only auditory or only visual stimuli. So, there is a potential that visual and auditory components interact to cause a systematic outcome for the uncanny valley, suggesting that the conceptual congruence assumption cannot be ruled out completely. Incongruency has less effect on uncanniness than modality in both age groups. Younger people are more sensitive to visual layering of naturalness but the older have a more general evaluation to multimodal stimuli.

5.2. Discussion of the Neuroimaging Experiment

5.2.1. Scope of the Neuroimaging Experiment

In this study, we investigated the spatiotemporal features of cortical hemodynamic responses of healthy adults during various types of audio-visual human and robot video stimuli and aimed to observe correlations between behavioural response and magnitude of hemodynamic activity in significantly activated PFC regions. The ultimate goal was to interpret the differences and similarities between neural correlates of emotional processing of human and robot faces and to explore whether the uncanny feelings elicited a proportional hemodynamic effect that could be quantified with fNIRS recordings.

5.2.2. Neuroimaging Studies on PFC

Previous fMRI studies demonstrated that human and robot stimuli elicited neural responses in specific brain regions such as fusiform gyrus and temporo-parietal junction^{223–225}. Prefrontal cortex, the most complex and executive part of the human brain, also has a role in perception and emotional processing steps in human-robot interactions (HRI). Ventromedial parts of the prefrontal cortex (vmPFC) are addressed with social cognition capabilities such as theory of mind and facial emotion cognition²²⁶. Hence, the role of vmPFC in social cognition can be expanded to human-robot interactions (HRI) as well. An experimental human-robot and human-human interaction paradigm elicited increased activity in vmPFC regions in a study performed by Wang et al. (2014)²²⁷.

Dorsolateral prefrontal cortex (DLPFC) and other PFC regions have indirect roles in emotion regulation and are involved primarily in regulation, integration and processing of executive functions such as cognitive control, emotion regulation, and secondarily abstract reasoning processes²²⁸. DLPFC lesions caused impaired auditory attention²²⁹. Lateral orbitofrontal cortex (IOFC) was also found sensitive to facial mimicry and has been shown to play a role in generating emotional response to human faces^{230,231}. However, a recent fNIRS study presented that artificially designed faces and facial expressions elicited less hemodynamic response than real human faces in OFC regions

5.2.3. Hemodynamic Activity of DLPFC and OFC

In our study, we found distinct neural responses to human and robot stimuli at DLPFC and OFC regions. Two channels which are located in the left DLPFC, one channel at right DLPFC and two channels in OFC areas showed significant hemodynamic activity during processing of different human and robot stimuli. Significantly active channels relevantly localize around the lateral parts of the PFC. The fact that our robot and human stimuli elicited significant hemodynamic responses at the DLPFC regions may be considered as a verification that our experimental design induced desired hemodynamic contrast in alignment with current literature and could be used to test our hypotheses.

Our results demonstrated that the hemodynamic response to human face stimuli was statistically significantly higher than the responses to robot face stimuli in Channels 6 and 14 which are located in the left DLPFC area. Human face is one of the main sources of social cognition as a strong representation of identity and emotional states with facial mimicry ²³². Higher hemodynamic response to stimuli involving human faces may be linked to the primary emotion regulation function of DLPFC ²²⁸. DLPFC areas have been shown to elicit significant cortical activation in response to human face stimuli in previous studies conducted with fMRI. Lower degrees of DLPFC activation to happy faces was observed in depression patients when compared to healthy controls ²³³. A recent study by Kelley et al. (2021) explored differences in hemodynamic activity during a paradigm involving a human to human eye contact and human to robot eye contact and found that human to human eye contact elicited greater DLPFC activity ²²⁴.

At the first glance, consistent localizations of active channels in DLPFC may be linked with emotional regulation of human faces. Another PFC region where stimuli involving human faces induced statistically significantly higher hemodynamic response than that of robot faces corresponded to Channel 22 which was located in the Orbitofrontal cortex (OFC) area. OFC areas are also sensitive to processing of human faces and face specific activation changes were observed in OFC during face selection tasks ²³⁴. OFC has also been shown to elicit activation in the infant brain during parenteral interaction which involves face and voice stimuli ²³⁵.

We may assume that rich emotional clues of human faces induce specific emotional processing responses in DLPFC and OFC regions which result with increased hemodynamic responses to human face stimuli. But robot face stimuli didn't create

significant hemodynamic responses, thus we can propose that robot faces are perceived as abstract concepts rather than emotional objects as supports DLPFC's secondary function of abstract thinking.

Robot voice stimuli elicited significant oxy-Hb deactivation, showed more decreasing hemodynamic responses to robot voice than human voice stimuli in an OFC channel (Channel 15) at our study. Several fNIRS neuroimaging studies indicated that conversation with robots creates complex PFC activity^{236,237}. However, unlike long-termed conversations; our robot voice stimulus contains just a few words and it is unidirectional. It was unexpected that short lasting robot voices elicited decreased hemodynamic activity, so we can conclude that OFC is sensitive to differences between human and robot voices even in a short term.

Robot voices can create avoidance in humans, then deactivating hemodynamic response would occur in OFC areas. Human tendency on natural human voices than artificial robot voices shown in several neuroimaging studies. OFC was found to be sensitive to human voices and impairment of OFC areas resulted in disruption of the voice identification process in the human brain^{235,238}. IOFC was also found sensitive to facial mimicry and roles on emotional response to human faces^{230,231}. On the other hand, a recent fNIRS study presented that artificial design faces and facial expressions elicited less hemodynamic response than real human faces around the OFC regions¹⁹⁴.

5.2.4. Behavioural Episode of Neuroimaging Experiment

Participants rated human and robot stimuli after the fNIRS recording, behavioural results in the form of uncanniness score were also evaluated. Human face-robot voice paired stimuli were rated as having the uncanny feelings, followed by robot face-robot voice and robot face-human voice stimuli (Table 3.3). Human face-human voice stimuli were rated as most normal. There is a clear contrast between the results that; incongruent human face-robot voice stimuli are the most uncanny, and congruent human face-human voice stimuli is the most normal.

Mismatch between face and voice creates discomfort and disharmony feelings in humans. Mismatch situation may trigger cognitive dissonance and results with uncanny feelings^{3,83}.

5.2.5. Limitations and Future Works

Our study has several limitations regarding experimental design and neuroimaging capacity. Present experimental design consists of videos involving a mix of human and robot face and voice stimuli in order to evaluate human-robot interactions. Real humans and robot models can be employed in real-life experimental conditions to evaluate interactions between humans and robots. In addition to robot face representation in videos, robot models allow interaction with all parts of the robot body and tactile sensation.

Our results are limited with hemodynamic activity of the PFC due to fNIRS device's channel capacity. Human and robot faces create PFC activity because of the emotion regulation and social cognition capabilities, more cerebral cortex areas such as temporoparietal junction and fusiform gyrus are addressed with human-robot interactions.

Advanced experimental paradigms which execute with real human and robot model conditions can provide rich emotional and behavioural clues. Whole brain imaging promises better spatial resolution for response to human-robot interaction in the cerebral cortex.

5.2.6. Conclusion

Here, we conducted an exploratory study of how human and robot faces are perceived and emotionally processed in the PFC with fNIRS method. PFC is one of the prominent brain areas where the high level cognitive processes such as emotion regulation, social cognition and identity of self are located ²²⁶. So, fNIRS is a convenient and portable neuroimaging method and allows quantifying human-robot interaction in the natural environment of participants. fNIRS also provides robust presentation of task-related hemodynamic activity in the human brain with minimised external noise ²³⁹.

In support of previous literature, DLPFC and OFC were found to be sensitive to processing of stimuli consisting of robot and human faces. Our primary and exploratory study gives clues about neuronal mapping of human and robot conditions in the PFC. For a future research direction, more participants and advanced experimental conditions make way to find hemodynamic markers and classify representation of human and robot faces in the human brain.

5.3. General Discussion

5.3.1. Behavioural Modality

The behavioural and fNIRS experiments have multi-layered outcomes on the sensory, emotional and age-related effect of the uncanny valley. Behavioural experiment results emphasized the following: (1) multimodal stimuli create increased uncanny valley effect, (2) voice stimuli could be a determinant factor as visual stimuli, (3) incongruity has smaller effect on uncanniness than modality and (4) the younger has detailed look on naturalness levels in contrast to the elder's linear response.

Unimodal auditory, unimodal visual and multimodal audio-visual stimuli scores on uncanniness were analysed to answer the main research question of how modality affects the uncanny valley effect. Only face and only voice conditions as unimodal stimuli are evaluated as preserving lower uncanniness than face-voice paired multimodal stimuli.

Both unimodal realistic faces and unimodal realistic voice stimuli have lower uncanniness scores than multimodal audio-visual realistic stimuli in all age groups. Unrealistic face - unrealistic voice multimodal stimuli have the highest uncanniness score but unimodal unrealistic face and unimodal unrealistic voice stimuli have both lower uncanniness scores than multimodal unrealistic face-voice stimuli. Unimodal only audio and only visual stimuli are seemed to elicit reduced uncanny feelings.

Based on the results above, we assume that multimodal audio-visual stimuli can generate stronger uncanny feelings than unimodal stimuli. Multimodal conditions, in which facial and speech components coexist, gave rise to the uncanny valley effects⁸⁴.

5.3.2. Possible Explanation of Uncanny Valley: Violation of Expectation Hypothesis

Human brain uses forms and templates about individual's living environment and encountered entities. Appearance of the agent has to be consistent with its motor actions and physical features like voice. When brain's prediction about the agent's consistent look contradicts with its actions and features; prediction error occurs at perceptual process. Neural response to conflicted agent's which create prediction error could be stronger^{240,241}. Prediction error could be occurred when brain process human-like agents. Human-like android agents and their motor actions generated stronger neural activity at parietal cortex regions as prominent uncanny valley& fMRI study showed³⁸.

It has been thought that humans tend to attribute humanistic characteristics to human-like agents, but when they realize that they possess certain characteristics that are not human-like, they find them uncanny. Prediction error to humanlike agents can give a cognitive explanation to uncanny valley, which is mentioned as Violation of Expectation hypothesis ²².

We detected stronger hemodynamic response to incongruent human face-robot voice stimuli than congruent robot face-robot voice stimuli at right DLPFC region (Channel 2) in neuroimaging study. Correlation between hemodynamic and behavioural response also found at left OFC region (Channel 22) to incongruent human face-robot voice stimuli. Our experimental stimuli don't contain motor actions. But they are consisted of congruent and incongruent face and voice pairs which are important features to agent's perception process. Enhanced hemodynamic activity to incongruence face and voice pairs may show that minor prediction error was occurred in neuroimaging experiment.

Older participants also rated real human stimuli less eerie and uncanny than realistic face designs in behavioural experiment. Thus, elder's discomfort with realistic designs may be linked to violation of their human concept. In light of our findings from both neuroimaging and behavioural experiments, we can propose that Violation of Expectation hypothesis is a possible explanation of uncanny valley effect.

5.3.3. Face Perception in PFC

fNIRS experiment results showed consistent PFC activity to human and robot faces and lateral parts of PFC were sensitive to hemodynamic changes with different human and robot stimuli. Robot voice altered hemodynamic deactivation compare with human voices in the DLPFC area, but human faces responded with more hemodynamic activity than robot faces at the same area.

In this study, behavioural and fNIRS experiment steps were set in order to explain the nature of human-robot interactions. Face and voice components are the major factors during the interaction. Facial features involve rich sources for social communication in humans and emotions of robots can be perceived from robot faces ^{242,243}. Thus, we can say that the face is a prominent visual component. Face research is built with emotion, visual perception and social communication works and using neuroimaging methods to investigate neural activity of face effect is an empowering step of the research ²⁴⁴.

Another main finding of our study was the significant correlation observed between hemodynamic activity of an OFC channel and behavioural response (Figure 3.9). At Channel 22, which is located at OFC, human face-robot voice > robot face-robot voice contrast had a significant correlation between behavioural and hemodynamic responses. Channel 22 also showed increased hemodynamic response to human face stimuli than robot face stimuli.

Human face is a specialized part of the body as for the perceptual process in the human brain; top-down modalities were employed during face perception²⁴⁵. Top-down modalities play an important role on face perception at different parts of the brain²⁴⁶. Behavioural and hemodynamic correlation of increased response to the human face may be a sign of integrated perception of the human face.

5.3.4. Face-Voice Mismatch

Voice is also an important component during human-robot interactions, but less study focuses on the voice effect. We evaluated both congruent and incongruent face-voice pairs of humans and robots. Incongruent pairs elicited more uncanny feelings in behavioural experiment and behavioural episode of neuroimaging experiment steps and incongruence effects were clear with human faces in both experiments. Humans tend to perceive face and voice together and at congruent form and if expectation to proper face-voice pairs breaks, cognitive dissonance may occur^{3,247}.

In line with behavioural response to face-voice mismatch effect, a right DLPFC channel (Channel 2) from our experiment detected significantly increased hemodynamic activity to incongruent human face-robot voice stimuli than congruent robot face-robot voice stimuli. Face-voice mismatch also altered neuronal activity in inferior frontal gyrus, which is the neighbouring area of PFC²⁴⁸.

We managed to collect behavioural responses to audio-visual modality, mismatch situation and age-dependent effects from our experiment and tried to localize human and robot stimuli in the PFC. In order to perform a detailed evaluation of how faces are perceived, multidimensional experimental settings had to be performed like the behavioural and neuroimaging experiment steps here.

5.3.5. Conclusion of the Thesis

Robots are gaining more and more visibility in our daily lives in recent years. Parallel to this, human-robot interactions are becoming more complex and multi-layered. As we give several examples about cognitive and neuronal response during human-robot interaction in previous parts, robots have an important effect to shape social cognition in humans today. Design of robots is one of the crucial elements of human-robot interaction.

In this research, we evaluated robot designs in detail and emphasized how visual and auditory components of robots were perceived. Thanks to behavioural and neuroimaging experiment steps, detailed evaluation of auditory and visual aspects of robots were done. As an outcome of the behavioural study, we assume that robot voices are nearly a determinant factor as robot faces during human robot interaction. This inference can contribute to voice component effects on uncanny valley research.

We also underlined congruent face and voice pairs that can be accepted easily in human robot interaction; our scientific outcome may support the generation of better face and voice pairs in robots with optimal designs. Our neuroimaging results showed consistent and localized hemodynamic activity of the PFC to human and robot stimuli. Mapping right and left lateral parts of the PFC as human and robot stimuli specific can be counted as promising steps.

In our study, except a right DLPFC channel (channel 2), all significant hemodynamic activity to human and robot stimuli were occurred at right DLPFC and OFC regions. Although any hemispheric lateralization study with human and robot paradigms haven't done yet, we detected novel left-dominant lateralization mapping of DLPFC and OFC to human and robot stimuli. These clues make a way to future hemispheric lateralization studies with uncanny valley effect.

Our study has some limitations. We used only 2D audio-visual stimuli which were presented from the computer screen. Experiments with 3D robots may provide rich and strong interactions and may give more complex cognitive clues. Our neuroimaging method covered only PFC areas of the human brain. To investigate human-robot interactions more inclusively; temporo-parietal cortex areas and occipital cortex have to be included into imaged brain areas.

In addition to cerebral cortex, limbic system components and mesencephalon regions are also primarily responsible for emotion generation ^{249,250}. For the deeper and integrated look on uncanny feelings; whole brain covered neuroimaging methods may be employed in the future studies.

At the final words; human-robot interactions are a multidimensional research topic and involves a wide variety of cognitive and neuroscientific clues. Robots are an important and promising element for us with their roles as helpers, assistants and companions in daily life. They are not threat, but friends. In the light of our research outcomes, it might be possible to design better robots to interact easily with humans in the future.



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7.APPENDICES

7.1 Ethical Approvals

YEDİTEPE ÜNİVERSİTESİ BEŞERİ VE SOSYAL BİLİMLER ETİK KURULU KOMİSYONU

04.11.2021 TARİHLİ
22/2021 No'lu TOPLANTI KARARLARI

- 1) Yeditepe Üniversitesi Mühendislik Fakültesi Bilgisayar Mühendisliği Bölümü Öğretim Üyesi Dr. Öğr. Üyesi Funda Yıldırım'ın baş araştırmacı olarak, Bilişsel Bilimler programında Doktora Öğrencisi Emre Yorgancıgil ve Lisans Öğrencisi Cansu Malak ile Computational Neuroscience and Visual Perception Lab'da gerçekleştireceği "Değişik Gerçekçilik Seviyelerindeki İnsan ve Robot Tasarımlarının Davranışsal Metotlarla Araştırılması" başlıklı araştırma projesinin Beşeri Bilimler etik standartlarına uygunluğu Yeditepe Üniversitesi Beşeri ve Sosyal Araştırmalar Etik Kurulu tarafından değerlendirilmiş ve onaylanmıştır.

YEDİTEPE ÜNİVERSİTESİ BEŞERİ VE SOSYAL BİLİMLER ETİK KURULU KOMİSYONU

04.11.2021 TARİHLİ
22/2021 No'lu TOPLANTI KARARLARI

Prof. Dr. Suat ANAR
Etik Kurul Komisyon Başkanı
İletişim Fakültesi, Gazetecilik Bölümü

Prof. Dr. Sultan ÜZELTÜRK
Hukuk Fakültesi, Hukuk Bölümü

Prof. Dr. Cengiz ERİŞEN
İktisadi ve İdari Bilimler Fakültesi, Siyaset Sistemi ve Uluslararası İlişkiler Bölümü

Prof. Dr. Demet LÜKÜSLÜ
Fen-Edebiyat Fakültesi, Sosyoloji Bölümü

Prof. Dr. Saffet BABÜR
Fen-Edebiyat Fakültesi, Felsefe Bölümü

İSTANBUL MEDİPOL ÜNİVERSİTESİ
GİRİŞİMSEL OLMAYAN KLİNİK ARAŞTIRMALAR
ETİK KURULU KARAR FORMU

Sayı : E-10840098-772.02-5249
Konu: Etik Kurulu Kararı

15/10/2021

BAŞVURU BİLGİLERİ	ARASTIRMANIN AÇIK ADI	İnsan ve Robot Yüzleri Algısının Davranışsal ve Nörogörüntüleme Yöntemleriyle İncelenmesi			
	KOORDİNATÖR/SORUMLU ARAŞTIRMACI UNVANI/ADESOVADI	Dr. KÜBRA SOĞUKKANLI KADAK			
	KOORDİNATÖR/SORUMLU ARAŞTIRMACININ UZMANLIK ALANI	Dr. Sinirbilim			
	KOORDİNATÖR/SORUMLU ARAŞTIRMACININ BULUNDUĞU MERKEZ	İstanbul			
	BESTEKLEYİCİ	-			
	ARASTIRMAYA KATILAN MERKEZLER	TEK MERKEZ <input type="checkbox"/>	ÇOK MERKEZLİ <input checked="" type="checkbox"/>	ULUSAL <input checked="" type="checkbox"/>	ULUSLARARASI <input type="checkbox"/>

İSTANBUL MEDİPOL ÜNİVERSİTESİ
GİRİŞİMSEL OLMAYAN KLİNİK ARAŞTIRMALAR
ETİK KURULU KARAR FORMU

Değerlendirilen Belgeler	Belge Adı	Tarih	Yerleşim Numarası	Dil
	ARAŞTIRMA PROTOKOLÜ/PLANI			Türkçe <input type="checkbox"/> İngilizce <input type="checkbox"/> Diğer <input type="checkbox"/>
	OLUR RAPOR FORMU			Türkçe <input type="checkbox"/> İngilizce <input type="checkbox"/> Diğer <input type="checkbox"/>
	BELGELENDİRİLMİŞ GÖNÜLLÜ OLUR FORMU			Türkçe <input type="checkbox"/> İngilizce <input type="checkbox"/> Diğer <input type="checkbox"/>
Karar Bilgileri	Karar No:1026	Tarih: 14/10/2021		
	Yukarıda bilgileri verilen Girişimsel Olmayan Klinik Araştırmalar Etik Kurulu başvuru dosyası ile ilgili belgeler araştırmanın gerekece, amaç, yaklaşım ve yöntemleri dikkate alınarak incelenmiş ve araştırmanın etik ve bilimsel yönden uygun olduğuna "oybirliği" ile karar verilmiştir.			

İSTANBUL MEDİPOL ÜNİVERSİTESİ GİRİŞİMSEL OLMAYAN KLİNİK ARAŞTIRMALAR ETİK KURULU

BASKANIN UNVANI / ADI / SOYADI	Dr. Öğr. Üyesi Mahmut TOKAÇ
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Unvanı/Adı/Soyadı	Ünvanlı Alanı	Kurumu	Çevre	Araştırma ile İlgili	Karar *	İmza
Dr. Öğr. Üyesi Mahmut TOKAÇ	Tıp Tarihi ve Etik	İstanbul Medipol Üniversitesi	<input checked="" type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input checked="" type="checkbox"/> <input type="checkbox"/>	Uygundur
Prof. Dr. Mete ÜNGÖR	Endodonti	İstanbul Medipol Üniversitesi	<input checked="" type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input checked="" type="checkbox"/> <input type="checkbox"/>	Uygundur
Doç. Dr. Mehmet Kemal ÖZDEMİR	Elektrik ve Elektronik	İstanbul Medipol Üniversitesi	<input checked="" type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input checked="" type="checkbox"/> <input type="checkbox"/>	Uygundur
Doç. Dr. İlknur KESKİN	Histoloji ve Embriyoloji	İstanbul Medipol Üniversitesi	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input checked="" type="checkbox"/> <input type="checkbox"/>	Uygundur
Doç. Dr. Devrim TARAKCI	Fizyoterapi ve Rehabilitasyon	İstanbul Medipol Üniversitesi	<input checked="" type="checkbox"/> <input type="checkbox"/>	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input checked="" type="checkbox"/> <input type="checkbox"/>	Uygundur
Dr. Öğr. Üyesi Neziha HACIHASANOĞLU ÇAKMAK	Biyokimya	İstanbul Medipol Üniversitesi	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input checked="" type="checkbox"/> <input type="checkbox"/>	Uygundur
Dr. Öğr. Üyesi Neriman İpek KIRMEZİ	Tıbbi Farmakoloji	İstanbul Medipol Üniversitesi	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input type="checkbox"/> <input checked="" type="checkbox"/>	<input checked="" type="checkbox"/> <input type="checkbox"/>	Uygundur

* :Toplamda Belirli

Bu belge, güvenli elektronik imza ile imzalanmıştır.
Evrakın <https://turkiye.gov.tr/istanbul-medipol-universitesi-ehys> linkinden 90342A9FX0 kodu ile doğrulayabilirsiniz.

7.2. Curriculum Vitae

Personal Informations

Name	Emre	Surname	YORGANCIGİL
Place of Birth		Date of Birth	

Education

Degree	Department	The name of the Institution Graduated From	Graduation year
Doctorate	Neuroscience	Institute of Health Sciences, Yeditepe University	2021
Master	-	-	
University	Faculty of Medicine	Süleyman Demirel University	2015
High school	-	Isparta Süleyman Demirel Science High School	2009

All the grades must be listed if there is more than one (KPDS, ÜDS, TOEFL; EELTS vs),

Languages	Grades (#)
English	80 (YDS, September 2018)

Work Experience (Sort from present to past)

Position	Institute	Duration (Year - Year)
Research assistant	Physiology Department, Faculty of Medicine, Yeditepe University	2015
Medical doctor/General practitioner	Maltepe Tuberculosis Facility	2016-2018
Medical data specialist	Acıbadem Technology	2019-2021

Computer Skills

Program	Level
Microsoft office	Good
MATLAB	Average
Python	Average
JASP	Average
Adobe Premiere	Basic

*Excellent , good, average or basic

Scientific works

The articles published in the journals indexed by SCI, SSCI, AHCI

Yıldırım Baş F, Bayram D, Arslan B, et al. Effect of alpha lipoic acid on smoking-induced skin damage. <i>Cutan Ocul Toxicol.</i> 2017;36(1). doi:10.3109/15569527.2016.1154069
Naziroğlu M, Kozlu S, Yorgancigil E, Uğuz AC, Karakuş K. Rose oil (from <i>Rosa × damascena</i> Mill.) vapor attenuates depression-induced oxidative toxicity in rat brain. <i>J Nat Med.</i> 2013;67(1). doi:10.1007/s11418-012-0666-7

Articles published in other journals

“Süleyman Demirel Üniversitesi Araştırma ve Uygulama Hastanesi’ne Başvuran Hastaların Aydınlatılma ve Onam Alınma Düzeylerinin Değerlendirilmesi”, Tuğçe Ertürk, Emre Yorgancigil, Süleyman Bozbıyık, Selin Çabuk, Gülhacer Görgün, Doğa Kaşhoğlu, İmran Mersin, İbrahim Emre Tunca, Hakkı Yıldırım, Süleyman Serhat Gürpınar, SDÜ Tıp Fakültesi Dergisi, 2013, ISSN 1300-7416, Cilt 20, Sayı 4: sayfa 144-148
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Proceedings presented in international scientific meetings and published in proceedings book.

“Audio-Visual Components and Cross-Generation Characteristics of Uncanny Valley”, Emre Yorgancıgil, Burcu A. Urgan, Cansu Malak, Funda Yıldırım, 43rd European Conference on Visual Perception (Virtual Symposium), 22-27 August 2021, Page: 104
“Investigating the Audio-visual Side of Uncanny Valley: A Cross-Generation Behavioural Study”, Emre Yorgancıgil, Funda Yıldırım, 7th International Symposium on Brain and Cognitive Science (Virtual Symposium), 31 May 2020, Page:65
“Uncanny Valley and Social Cognition”, Emre Yorgancıgil, Hakan Atalay, Poster Presentation in The European Conference for Cognitive Science 2019, 2-4 September 2019, Bochum- Germany, Page:172
“Investigation of Loneliness Levels in the International Students”, Mustafa Saygın, Arif Demirdaş, Çağrı Cafer Korucu, Emre Yorgancıgil, ACTA PHYSIOLOGICA, ISSN 1748-1716, Volume: 215, Page:109, Special Issue:SI, Meeting Abstract:PC232, Published:SEP 2015

Others (Projects / Certificates / Rewards)

Laboratory Animal Research Certificate, Yeditepe University-2018
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