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Implications of Magnetic Resonance Imaging (MRI) for Economic Research and the Development of Neuromanagement and Neuromarketing

ABSTRACT

The syncretism of traditional economic theory, based on hypothetical-deductive reasoning, with contemporary behavioral economics – which considersthe psychological and social aspects of consumer behavior – and the application of experimental economic tools and modern neuroeconomics research methods contribute to a better understanding of the economic decision-making process. The aim of this study was to determine the specificity and applicability of magnetic resonance imaging (MRI) as a tool in management and economic research, and to define the role of neuroimaging in the development of neuromanagement and neuromarketing. The article also aims to draw attention to the evolving methodology of economic research and the advancement of research techniques, including those in the field of imaging diagnostics. The foundation of modern neuroeconomics is, therefore, an interdisciplinary research approach. The analysis was conducted from an interdisciplinary perspective, with an attempt to syncretize economic and medical knowledge. The physical principles of MRI were presented, an MRI examination was described – including medical indications and contraindications –, and the implications of MRI and functional MRI (fMRI) for economic sciences and management were discussed. Functional MRI techniques are used to test consumer responses to specific stimuli by measuring changes in the activity of the prefrontal cortex, amygdala, and hippocampus. The findings indicate that the ventral striatum is associated with the reward system, the orbitofrontal cortex modulates desire, the medial prefrontal cortex is responsible for positive social responses, the posterior cingulate cortex is involved in conflict processing, whereas the amygdala controls threat and fear-based behaviors in humans. The results of neuroimaging using fMRI are particularly important in the field of neurofinance, neuroaccounting and neuromarketing.

KEYWORDS: neuroeconomics, neuromanagement, neuromarketing, Magnetic Resonance Imaging (MRI); behavioral economics

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STRESZCZENIE

Implikacje wykorzystania rezonansu magnetycznego (MRI) w badaniach ekonomicznych oraz rozwoju neurozarządzania i neuromarketingu

Synkretyzm tradycyjnej ekonomii bazującej na metodzie hipotetyczno-dedukcyjnej oraz współczesnej ekonomii behawioralnej uwzględniającej aspekty psychologiczno-społeczne zachowań konsumentów z jednoczesnym wykorzystaniem narzędzi ekonomii eksperymentalnej oraz nowoczesnych metod badawczych neuroekonomii pozwolił na znacznie lepsze zrozumienie i wyjaśnienie uwarunkowań procesu podejmowania decyzji ekonomicznych. Celem rozważań podjętych w artykule jest określenie specyfiki i użyteczności rezonansu magnetycznego MRI jako narzędzia badawczego wykorzystywanego w badaniach ekonomicznych, a także określenie roli neuroobrazowania w rozwoju neurozarządzania i neuromarketingu. Celem artykułu jest także zwrócenie uwagi na zmieniającą się metodologię badań ekonomicznych i stosowanie coraz bardziej wyrafinowanych technik badawczych, w tym z zakresu diagnostyki obrazowej. Fundamentem współczesnej neuroekonomii jest więc interdyscyplinarne podejście badawcze. Przedstawione podejście badawcze ma charakter interdyscyplinarnych deliberacji. Stanowi bowiem próbę synkretyzmu wiedzy ekonomicznej i medycznej. W artykule przedstawiono fizyczne podstawy obrazowania rezonansu magnetycznego, omówiono przebieg badania z uwzględnieniem medycznych wskazań i przeciwskazań do obrazowania, a także podjęto próbę identyfikacji implikacji zastosowania MRI i fMRI na gruncie nauk ekonomicznych i zarządzania. Podstawowymi miarami wykorzystywanymi do testowania reakcji na określone bodźce przy użyciu fMRI jest aktywacja kory przedczołowej, ciała migdałowatego i hipokampa. Na podstawie uzyskanych wyników można stwierdzić, że brzuszne prążkowie odpowiada za układ nagrody, kora oczodołowa za pragnienie posiadania, przyśrodkowa kora przedczołowa za pozytywną więź, kora tylnego zakrętu obręczy za konflikt, natomiast ciało migdałowate za wyzwanie i zagrożenie. Uzyskiwane wyniki neuroobrazowania przy użycia fMRI są szczególnie istotne w obszarze neurofinansów, neurorachunkowości i neuromarketingu.

SŁOWA KLUCZE: neuroekonomia, neurozarządzanie, neuromarketing, rezonans magnetyczny (MRI), ekonomia behawioralna

Introduction

The history of economic thought and contemporary research trends in economics as a social science indicate that in a complex economic, political and social reality, the traditional economic paradigm does not always adequately or comprehensively describe and explain dynamic changes of a rapidly globalizing world. In the absence of comprehensive evaluations of economic reality, predictions cannot be formulated on the basis of theoretical and empirical research results. The rapid pace of civilization's development suggests that the mainstream economic paradigm needs to be modified. According to the principles of the philosophy of science (general methodology), economics must meet fundamental criteria in order to be considered a scientifically rigorous discipline (Ajdukiewicz, 1985). These include strong rationality, high explanatory, prognostic, and heuristic power, high theoretical adequacy (Popper, 2005), and intersubjective testability and communicability (Frankfort-Nachmias & Nachmias, 2001). Science is not about collecting data, but about solving research problems. Methodology is the study of the methods used in science and the conditions of their validity. According to M. Blaug, methodology is a field of knowledge aimed at mastering cognitive structures of science (Blaug, 1995). S.C. Dow argues that methodology is the field of science that deals with the foundations of economic cognition (Dow, 2002).

The management of limited resources constitutes a fundamental problem in economic research. Contemporary behavioral economics, along with its derivative field of neuroeconomics, focuses on human cognition in the economic decision-making process. This study was conducted under the assumption that the existing body of empirical evidence in neuroeconomics can significantly contribute to the development of contemporary economics and enhance its scientific rigor. The use of magnetic resonance imaging (MRI) in economic studies fosters the development of economic decision-making support systems that rely on neuroimaging results. It can be assumed that medical sciences (particularly electroradiology and neuroradiology) and economic disciplines (especially experimental and behavioral economics) can promote more holistic approaches in theoretical and cognitive research, while also facilitating the implementation of optimal solutions in economic practice.

Contemporary neuroscience is an interdisciplinary field that analyzes the biological aspects of human behavior in the context of neural networks and the central nervous system. Neuroscience integrates knowledge from medicine, biology, biophysics, biochemistry, information technology, and psychology (Squire, 2013). Cognitive neuroscience, in turn, combines psychological knowledge about cognitive processes with research into brain function (Gazzaniga & Ivry, 1998). Cognitive neuroscience seeks to explore the cognitive aspects of human brain functioning using a mechanistic approach (Gazzaniga, 1995). Brain imaging techniques are also increasingly applied in economic sciences. Neuroeconomics is a dynamically growing subfield of economics. Research in neuroeconomics focuses on decision-making under conditions of risk and uncertainty, delayed reinforcement, morality in economic decision-making, as well as economic activities undertaken by individuals (consumers) and entire societies (collectives). Therefore, there is a need to develop a unified scientific theory to explain the purchasing behaviors of market actors. In interdisciplinary research teams, economists and psychologists observe the behaviors of market participants and develop models that explain them, while neurobiologists used specialized research tools to investigate the biological mechanisms underlying consumer decisions (Glimcher & Rustichini, 2004). In neuroeconomics research, non-invasive medical procedures are employed to comprehensively analyze brain activity in every stage of the decision-making process under controlled experimental conditions, generating economic brain maps that depict the activity of different brain areas correlated with consumer decisions (Glimcher et al., 2009).

The aim of the article is to determine the specificity and usefulness of MRI as a research tool used in economic research, as well as to determine the role of neuroimaging in the development of neuromanagement and neuromarketing. In response to the research objective formulated in this way, the following problem (research) questions were posed: 1) What is the MRI method and what is its specificity? 2) What is the physical basis of MRI? 3) What are the indications and contraindications for MRI neuroimaging? 4) What is the usefulness of MRI in economics, management, and marketing? In the implementation of research goals and collecting literature, traditional browsers were used: Google Scholar (http://scholar.google.com/) and ResearchGate (https://www.researchgate.net/), using keywords such as: MRI, fMRI, neuromarketing literature review, neuromanagement literature review. Literature research was used to emphasize the growing role of a holistic research approach to consumer analysis and to show the usefulness of the fMRI method in economics, management, and marketing.

In recent years, the use of various neuroimaging methods, including fMRI, in marketing, management, and economics has been gaining increasing popularity. The usefulness of scientific data and research results is confirmed by systematic reviews of the literature and bibliometric analyses carried out by, among others, A.H. Alsharif et al. (2023), G.V. Jayavardhan and N. Rajan (2023), W.M. Lim and M.A. Weissmann (2023), G. Srivastava and S. Bag (2023), P. Tirandazi et al. (2023), A. Byrne et al. (2022), T. Asunakutlu and T. Aydoğan (2022), J. Siddique et al. (2022), L. Robaina-Calderín and J.D. Martín-Santana (2021), A.H. Alsharif et al. (2021), W.M. Lim et al. (2021), R. Sharma and A. Sinha (2020). Neuroimaging using fMRI is primarily used to identify key factors (stimuli) influencing consumer purchasing decisions, assess the course of the decision-making process, consumer engagement, and behavioral control (Schäfer & Marten, 2021; Wollenweber, 2021; Aditya & Sarno, 2018; Alvino et al., 2020; Alvino, 2019; Karim, 2019; Rutkowska, 2022).

A review of the literature indicates that the fundamental nature, technological aspects, and the course of MRI examinations are largely overlooked in studies that focus on neuroimaging in economic research. Meanwhile, a solid understanding of the physical principles of MRI and brain imaging (scanning) techniques is essential for fully grasping the foundations of neuroimaging and assessing the potential implications of MRI for economic research. To address this knowledge gap, the main aim of this study was to present the technical aspects of MRI and analyze its applicability for economic research. The article is a review. It presents the physical principles of MRI, describes the MRI examination process – including medical indications and contraindications for the procedure – and discusses the implications of MRI and functional MRI (fMRI) for the economic sciences. The applicability of fMRI brain scans in neurofinance, neuroaccounting and neuromarketing was analyzed based on a review of the literature.

In contemporary neuroeconomics, research into advanced brain imaging techniques is spurred not only by intellectual and scientific curiosity, but also by the pursuit of pragmatic solutions in business practice. The results of MRI scans have potential applications in neuromanagement, neurofinance and neuromarketing. A thorough understanding of the specific characteristics of different MRI techniques, the theoretical and physical principles of MRI, and brain physiology facilitates the development of optimal protocols for empirical investigations that contribute to achieving specific research objectives. Modern research techniques and methods in experimental economics, including behavioral economics, not only deepen the foundations of the theoretical understanding of the potential of the human intellect and the rationality of consumer behavior, but also open new avenues for implementing innovative solutions in business practice.

Physical principles of magnetic resonance imaging

Magnetic resonance is a phenomenon that can be explained based on the laws of quantum mechanics. Nuclear magnetic resonance (NMR) imaging relies on the quantum-mechanical properties of atomic nuclei (Canet, 2019). The resonance phenomenon involves the interaction between atomic nuclei, a magnetic field, and an electromagnetic wave. Resonance occurs only in atomic nuclei with unpaired electrons. Most atomic nuclei rotate rapidly around their axes and have a magnetic moment that arises from the spin of protons and neutrons. Nuclear spin is determined by the speed of nuclear rotation is a characteristic feature of an atom. Nuclear magnetic resonance occurs only in nuclei with non-zero spin. The nucleus of a hydrogen atom ^1H, the most abundant element in biological systems, has the greatest magnetic moment. The nucleus of a hydrogen atom contains one proton, which is why NMR is also referred to as proton or hydrogen NMR. Hydrogen protons are also used in proton magnetic resonance spectroscopy (Pruszyński, 2015; Zhu & Barker, 2011).

Magnetic resonance imaging relies mainly on hydrogen atoms. When a nucleus in an external magnetic field is excited by an electromagnetic pulse (wave) at the resonance frequency, energy is absorbed and some of the protons move to a higher energy state. As a result, the direction of a proton's magnetic moment (vector) shifts from parallel to anti-parallel relative to the external magnetic field. After excitation, the magnetization vector gradually returns to its initial state. The resulting radiofrequency (RF) radiation is detected and converted into images of the examined anatomical structures. Magnetic resonance imaging relies on the magnetic properties of atomic structures and radiant energy, provided that there is an interaction between atomic nuclei and the applied magnetic field. This interaction is referred to as the resonance condition (Cichocka, 2015). Spatial and temporal fluctuations in the magnetic properties of atomic nuclei are detected in magnetic fields, and the correlations between these fluctuations, their structure, and their effects on the cellular environment are analyzed. Based on these properties, tissues can be differentiated in terms of their morphology, metabolism and function, which is particularly useful in examinations of cognitive processes and in neuroimaging. Cross-sectional images of the examined anatomical structures are generated by analyzing the following basic parameters: spin density (ρ), spin relaxation times (T1 and T2), chemical shift ratio (σ), self-diffusion coefficient (δ) and magnetic susceptibility (χ).

The MRI method is based on the assumption that an atomic nucleus with an odd number of protons and neutrons has its own angular momentum. A nucleus with non-zero spin rotates around its own axis and generates a magnetic field. Each nucleus has a magnetic moment μ, and the total magnetic moment of a group of nuclei equals $M = 0$. The magnetic moments of protons per unit of volume is referred to as magnetization M. The magnetic moment of a nucleus μ is proportional to its spin ($\mu = \gamma s$), where γ is the proportionality constant referred to as the gyromagnetic ratio of a nucleus. Magnetic moments are randomly oriented, and they become organized only in the presence of an external magnetic field with magnetic induction B_0. In this field, spins begin to precess and align in either a parallel or anti-parallel orientation to the magnetic field line. In this case, the total magnetic moment becomes greater than zero ($M > 0$), and its value depends on the type of nucleus and the magnitude of an external magnetic field. In the absence of an external magnetic field $B_0 = 0$, spinning nuclei can adopt any orientation. However, when the examined object is placed in an external magnetic field $B_0 = 0$, the nuclei begin to interact with this field. The spin precession frequency is directly proportional to the magnetic field induction and is also influenced by the gyromagnetic ratio of the nucleus. This relationship is described by the Larmor formula:

$$B_0 = \gamma\omega_0 \text{ for } \omega_0 = 2\pi f_0$$

where:

B_0 – magnetic field induction,
γ – gyromagnetic ratio,
ω_0 – angular frequency,
f_0 – precession frequency.

Precession frequency f_0 is also the resonant frequency of a nucleus. The magnetic resonance phenomenon relies on the Larmor frequency. The resonance condition – where the magnetization vector can deviate from its equilibrium orientation in an RF magnetic field – plays a key role in MRI (Pęczkowski, 2012). Protons possess potential energy when a constant external magnetic field is applied. Protons aligned parallel to the magnetic field line are in a lower energy state, whereas protons aligned anti-parallel are in a higher energy state. In magnetic resonance, protons transition between these states when an external source of energy is applied. Resonance conditions are described using quantum theory.

In MRI, excitation occurs only when a magnetic field with a resonant frequency is applied. The magnetization vectors of all atoms are synchronized. When the sample is excited by a pulse of a specific frequency, the magnetization vectors rotate in the same phase, and the transverse magnetization vector – i.e. the signal generated by the atoms – can be observed macroscopically. Excitation ends when the magnetization is fully aligned in the transverse plane. This is followed by relaxation of magnetization during which the spins return to their equilibrium state. Magnetic resonance imaging relies on two important phenomena: the decay of the transverse component of the magnetization vector to zero, and the return of the longitudinal component to equilibrium.

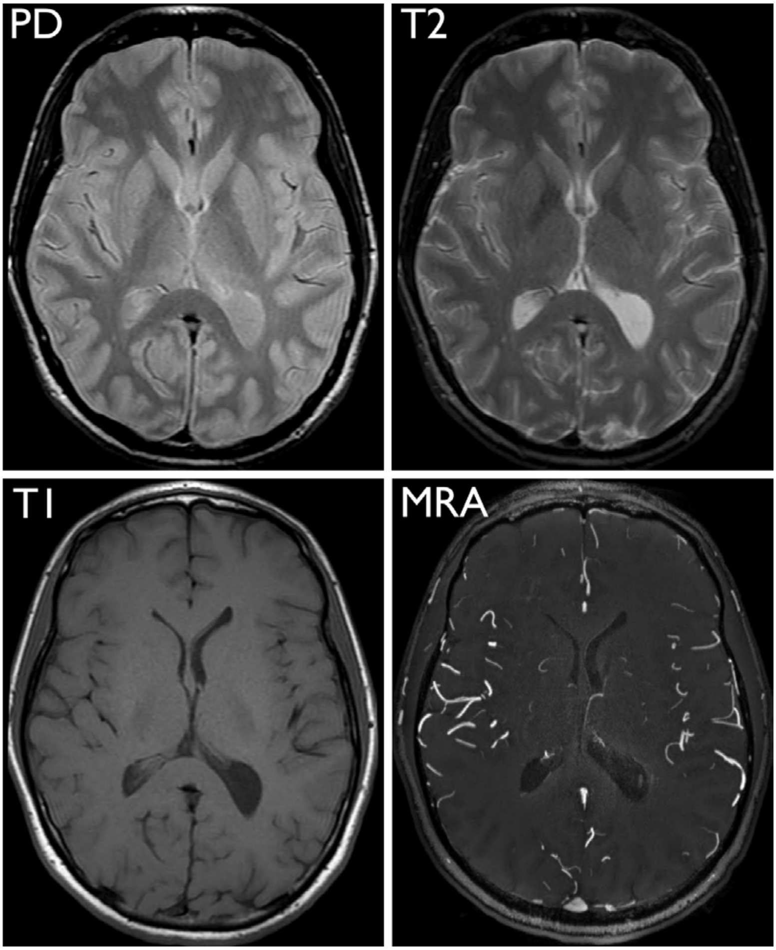
Longitudinal relaxation and transverse relaxation play a fundamental role in MRI. An object positioned in an external magnetic field B_0 is exposed to an electromagnetic wave B_1, with a frequency identical to the precession frequency described by the Larmor formula. This frequency corresponds to the radio wave frequency, which is why the electromagnetic pulse is referred to as the RF pulse. The generated energy is absorbed by the examined object. The RF pulse causes the vector to rotate, and the amount of that rotation is expressed by the flip angle (FA), which is influenced by the amplitude and duration of the RF pulse. The magnetization vector moves in a spiral path when the precessions induced by field B_0 and field B_1 overlap. The longitudinal component decays, and the transverse component returns to its original position. At a flip angle of 90°, the longitudinal component equals zero, and the transverse component reaches its maximum value. When the RF pulse is discontinued, the system returns to its initial state, and energy is emitted to the environment, i.e. the lattice. This process is known as longitudinal relaxation or spin-lattice relaxation. In field B_0, the longitudinal component is recovered exponentially, and its recovery time is determined by the interactions between nuclei and the lattice. The recovery of the longitudinal component proceeds differently in various tissues. During longitudinal relaxation time (T1), spins move from an anti-parallel to a parallel orientation (lower energy state), and this process is influenced by the rate at which energy is exchanged between nuclear spins and the lattice. Time T1 is highly correlated with the induction of field B_0, and it decreases in the presence of paramagnetic ions. The magnetization vector returns to its equilibrium position in a spiral path. A receiver coil is placed near the examined object to collect a free induction decay (FID) signal with a frequency equal to the Larmor frequency and a decreasing amplitude. When a 90° RF pulse is applied, the longitudinal component of the magnetic moment M decays to zero, and the transverse component increases. In the absence of the impulse, the longitudinal component recovers, and the transverse component decays. Magnetic resonance images are generated by inducing an FID signal in the receiver coil (Pruszyński, 2015).

Longitudinal relaxation is also accompanied by transverse relaxation. Transverse relaxation is also referred to as spin-spin relaxation because it relies on the mutual interactions between nuclear spins. When the RF pulse is discontinued, spins lose precessional coherence and transverse magnetization decays. In tissues where the random motion of particles is weak, spin-spin interactions are stronger and the relaxation process is shorter. In tissues with high water content, particles move very rapidly, but their mutual interactions are weaker and relaxation time is prolonged. This process decreases exponentially, and it is described by the constant value T2 which is characteristic of a given tissue. A supermagnetic ion shortens relaxation time T2. The magnitude of the electromagnetic field does not affect T2, but it does influence T1 (Pruszyński, 2015). The resonant absorption of RF energy is referred to as nuclear magnetic resonance (NMR).

In summary, magnetic resonance relies on three factors: the examined object, a magnet generating a uniform magnetic field B_0, and a transmission system that emits RF pulses at a frequency equal to the Larmor frequency in the direction of the examined object. These factors are required for resonant energy absorption. T1 relaxation time (longitudinal), T2 relaxation time (transverse), and their impact on the intensity of the registered signal, play a fundamental role in MRI.

To visualize the examined layer and assign grey-level values to successive points in the image, the analyzed area has to be exposed to pulse sequences and pulsed field gradients, and a spin echo pulse sequence has to be obtained. The MRI sequence defines a characteristic series of RF pulses with a given amplitude and bandwidth, gradient system settings, and the transmit/receive function of the RF coil. The applied MRI sequence determines the specificity of the acquired image. An image is obtained by selecting the appropriate MRI sequence and parameters, including: time of echo (TE), i.e. the time between the delivery of the RF pulse with a given FA and the reception of the echo signal; time of repetition (TR), i.e. the interval between successive pulse sequences applied to the same slice; time of inversion (TI), i.e. the time between the preparatory 180° pulse and the 90° readout pulse; and flip angle (FA), i.e. the rotation of the magnetization vector by an RF pulse. The basic physical parameters of MRI sequences – TE, TR, TI, and FA – determine the character of the obtained image (Bartusik-Aebisher, 2018). Selected MRI scans of the brain acquired in the axial (transverse) plane at the same head level are presented in Figure 1.

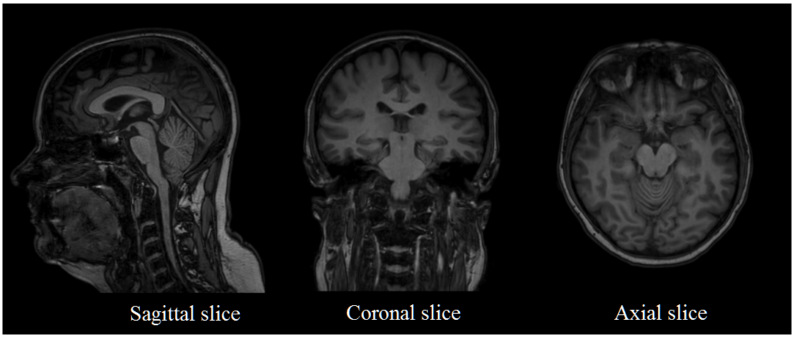
Figure 1. MRI scans of the brain acquired in the axial plane at the same head level: proton density (PD)-weighted image (top left), T2-weighted image (top right), T1-weighted image (bottom left), and magnetic resonance angiography (MRA) image (bottom right).



Source: Hess, Ch. *Exploring the Brain: How Are Brain Images Made with MRI?* Retrieved from: https://radiology.ucsf.edu/sites/radiology.ucsf.edu/files/blog/2012/04/MRI_brain.jpg (access: 05.05.2022).

Proton density-weighted, T1-weighted, T2-weighted, and MRA images differ in contrast, which provides information about various brain structures. Contrast refers to the difference in brightness between light and dark areas in the acquired image. In MRI, areas with high signal intensity appear bright, those with low signal intensity appear dark, and areas with intermediate signal intensity are typically grey. Tissues with high transverse magnetization appear brighter due to a higher signal amplitude, whereas tissues with low transverse magnetization appear darker due to a lower signal amplitude. Contrast plays a crucial role in neuroimaging. T1-weighted MRI scans of the brain acquired in the sagittal, coronal and axial planes are presented in Figure 2.

Figure 2. T1-weighted MRI scans of the brain acquired in the sagittal, coronal and axial plane



Source: Balasa, A. *Rezonans magnetyczny (MRI)*. Retrieved from: https://chiari.pl/diagnostyka/obrazowa/ (access: 05.05.2022).

A magnetic resonance imaging system consists of several structural components. The MRI unit includes a superconducting magnet (which generates a strong magnetic field above 0.5 T), a permanent magnet (which generates a magnetic field up to 0.3 T), or a resistive electromagnet (which produces a constant magnetic field). It also comprises gradient coils which generate gradient fields, compensating coils, volume (transmit-receive) or surface coils, an electromagnetic (radio frequency) transmitter, a frequency amplifier, a receiver module, a digital data processing system, and a Faraday cage that shields the MRI scanner from external electromagnetic interference.

There are two types of MRI scanners: open systems which allow access to the patient on all sides during the examination, and closed systems, where the patient is positioned inside a tunnel. MRI units can also be classified based on the strength of the magnetic field they generate: low-field scanners (up to 0.4 T), in which a constant magnetic field is created by a permanent magnet) or high-field scanners (0.7 to 3 T), in which a constant magnetic field is created by a superconducting magnet). The technical specifications and quality of an MRI scanner are crucial, particularly in brain imaging. An MRI unit with a field strength of 3 T emits much more energy which is absorbed by the body, resulting in body tissues receiving four times more heat than during a scan performed with a 1.5 T unit. For this reason, low-field units are considered safer for both patients and radiologists. A 1.5 T MRI unit also consumes less energy, making it more environmentally-friendly. Additionally, low-field scanners also generates less noise because the main magnetic coil produces only half as much energy as a 3 T unit. As a result, low-field scanners are less stressful and more comfortable for patients. A 1.5 T unit is also better suited to brain imaging because it reduces motion artefacts caused by patient movement during the examination. This is particularly important in functional magnetic resonance imaging (fMRI), which is often used to predict consumer behavior. fMRI examinations require close cooperation between the patient and the electroradiology technician. In summary, hardware parameters and the availability of imaging equipment should be considered when selecting a medical facility for neuroeconomics research.

Requirements, precautions and preparation for an MRI examination

Magnetic resonance imaging is a technique that relies on a very strong magnetic field. To ensure the safety of the patient, the operator, and the MRI equipment, potential contraindications and disqualifying factors must be identified before the examination. During the medical interview, the patient is required to complete a screening questionnaire. Disqualifying factors include the presence of electrically, magnetically or mechanically activated implants in the patient's body. As such, individuals with artificial cardiac pacemakers, neurostimulators, cochlear implants, orthopedic implants (screws, wires, stabilizers) and metallic dental implants are generally not eligible for MRI examinations. Other contraindications include infusion pumps, insulin pumps, metallic foreign bodies, and metal shavings in the eyes. Ferromagnetic implants, such as vascular clips and staples, can cause soft tissue burns and induce electric currents. The magnetic field can also interfere with or even severely damage electromechanical implants, posing a serious risk to the patient's health.However, orthopedic implants, vascular clips, prosthetic grafts, and stents made from non-ferromagnetic materials do not generally disqualify a patient from undergoing an MRI scan. An MRI examination can be relatively lengthy, and the experience of lying in a narrow tube inside the MRI machine may trigger claustrophobia in some individuals. Therefore, only patients who meet stringent safety criteria are eligible for MRI examinations (Rummeny et al., 2010; Saba, 2016).

Despite their immense diagnostic value, neuroimaging methods, including MRI, have certain limitations. One of the main challenges is the presence of artefacts, which can compromise image quality. To minimize artefacts and ensure optimal scan results, proper patient preparation and adherence to safety protocols are essential. Strict safety procedures must be observed in the MRI scanning room. The MRI unit is housed within a Faraday cage to shield it from external electromagnetic interference and to prevent zipper artifacts. Metal objects and items that are susceptible to magnetic fields – such as watches, keys, jewelry, magnetic cards, mobile phones – are strictly prohibited in the MRI room. Clothing must be free of metal elements, including zippers, buttons, clips, belt buckles, and wires. Given the strength of the electromagnetic field generated by the MRI scanner, occupational health and safety regulations must be rigorously observed to protect both the patient and the technician, as well as to prevent damage to the scanner and surrounding equipment. Effective cooperation between patient and the electroradiology technician during an MRI or an fMRI examination. In fMRI procedures, patients must carefully follow the technician's instructions, which should align with the protocol and the specific objectives of the neuroimaging exam.

Contemporary MRI techniques used in neuroimaging

A number of innovative MRI techniques are currently deployed in neuroimaging to acquire information about brain morphology and neural function (Modo and Bulte, 2011). The most advanced methods include magnetic resonance spectroscopy (MRS), which provides information about brain tissue metabolism (Huettel et al., 2013), and fMRI which measures brain activity and evaluates brain function (Huettel et al., 2013). Diffusion-weighted imaging MRI (DWI-MRI) is also widely used to map brain structures. This technique visualizes the microstructure of white matter and the connections between nerve cells – features not detectable with with other imaging modalities – by measuring the Brownian motion of water molecules, which is influenced by the parameters of the surrounding tissue (Thijs et al., 2001). Diffusion tensor imaging (DTI) also delivers satisfactory results. It quantifies anisotropic diffusion within the central nervous system, traces the pathways of nerve fibers in the organized structure of white matter, and provides quantitative data on neural tissue function in the brain (Basser et al., 2000). Perfusion magnetic resonance (pMR) is yet another useful neuroradiological technique for measuring the blood flow rate (perfusion) in brain capillaries and evaluating cerebral microcirculation (Aksoy and Lev, 2020). Given the wide array of neuroimaging techniques and the rapid advancements in neuroradiology, the applicability of MRI for research purposes is likely to continue growing in the future (Siwek, 2015).

Only individuals who meet strict safety criteria can participate in neuroimaging studies. During a detailed medical interview, the participant is asked to fill in a screening questionnaire. In the next stage, an electroradiology technician prepares the participant for the examination. The individual is positioned on the MRI table, and a receive-transmit coil is placed over the head. The coil detects signals and enables the reconstruction of brain images during an fMRI exam. The table then slides into the tunnel of the MRI scanner, and the selected anatomical structures are examined in accordance with the appropriate research protocol.

Functional MRI (fMRI) is a non-invasive technique for measuring and evaluating brain activity. It combines conventional MRI scanning with measurements of blood flow in the examined organ. While MRI relies on the magnetic properties of hydrogen nuclei (Parizel et al., 2011), fMRI detects hemodynamic changes in capillaries. Local blood flow is strongly linked to the activity of neural tissue in the central nervous system. Neuronal activity requires energy, which is supplied through chemical reactions involving glucose and oxygen. Local cortical stimulation is accompanied by a local increase in blood flow and volume, which result in a local increase in blood volume and oxygen levels – visualized in the scan.

In fMRI, brain activity is assessed by analyzing how hemoglobin molecules – depending on whether or not they are bound to oxygen – respond to the magnetic field. Active regions of the brain require more oxygen, leading to a local accumulation of oxygen-bound hemoglobin. As a result, active and less active regions are visualized based on differences in the strength of the MRI signal. Blood-oxygen-level-dependent imaging (BOLD-contrast imaging) reflects variations in blood oxygenation at different levels of neuronal activity. Oxygenated hemoglobin – oxyhemoglobin (with the bound oxygen) and deoxygenated hemoglobin – deoxyhemoglobin (without the bound oxygen) have different magnetic properties (Ogawa et al., 1990). Oxyhemoglobin is diamagnetic, whereas deoxyhemoglobin is paramagnetic. Deoxyhemoglobin acts as a natural MRI contrast agent because it amplifies the signal emitted by nearby water molecules.

A local increase in oxygen levels during neuronal activity raises the oxyhemoglobin to deoxyhemoglobin ratio relative to periods of neuronal inactivity. As a result, oxyhemoglobin and deoxyhemoglobin produce different signals, which are registered by the coil and are used to identify brain areas where energy-intensive processes are taking place. During an fMRI exam, different regions of the brain are stimulated using a predesigned experimental paradigm, i.e. an algorithm based on which the patient is required to perform specific tasks. Subjects are generally presented with stimuli in blocks, where activity blocks are alternated with rest (control) blocks, and each block has the same duration of several dozen seconds. Differences in the intensity of the MRI signal are observed when the patient performs tasks that engage a given region of the examined organ (in particular the brain) and tasks that do not require such engagement. Signal intensity is compared, and the relevant data are processed to generate maps of cortical activity. It should be noted that fMRI detects regions where brain activity both increases and decreases during the performed task. Changes in blood flow and blood oxygenation are registered with a delay of approximately five seconds relative to the increase in neuronal activity; these are referred to as the hemodynamic response. The fMRI approach relies on the ultra-fast echo-planar imaging (EPI) sequence because changes in activity occur rapidly, and signal intensity changes by around 2–5% in 1.5 T scanners and 15% in 4 T scanners. In the EPI sequence, TE times approximate T2 relaxation times.

In summary, MRI is a non-invasive imaging method for evaluating the structure and function of the examined organ. In fMRI examinations, minimal differences in cortical blood flow are visualized during cognitive processes when the patient performs specific tasks. Morphological and functional differences are registered as brain structures are scanned by a magnetic resonance unit. These differences are then digitally processed and visualized in the form of maps or three-dimensional models of the brain, where the cortical regions activated during cognitive tasks are marked in color. It should also be noted that during an fMRI examination, brain functions are measured indirectly rather than directly. This fundamental modality plays an important role in economic research, as the decision-making process is evaluated and non-economic determinants of consumer decisions are identified based on the rate and volume of blood flow in the brain and the activation of nervous tissue.

Applicability of magnetic resonance in neuroeconomics

An interdisciplinary approach to analyses of economic processes increases the explanatory potential of economic sciences. Enhanced cognitive realism should promote a better understanding of economic processes and more effective forecasting of economic events (Polowczyk, 2010). According to Camerer and Loewenstein (2004), economic models are simplified descriptions of reality that are based on the assumption of rationality, and they will eventually be replaced by behavioral models (Camerer and Loewenstein, 2004). Behavioral economics is a relatively new field of economics that aims to validate the assumptions of neoclassical economics based on the results of sociological and psychological research (Kirkpatrick & Dahlquist, 2007). Neuroeconomics encompasses several fields of study with important theoretical and practical implications, including neurofinance, neuroaccounting and neuromarketing.

Neurofinance is an emerging interdisciplinary field of study in economics (Ostaszewski & Kosycarz, 2014). Neurofinance and behavioral finance research has revealed numerous empirically documented anomalies in classical financial theory, which undermine the assumptions of the existing financial paradigm (Akerlof & Shiller, 2009). Strictly economic problems are explained using methods applied in medical and natural sciences. Neurofinance combines financial, psychological and neurobiological knowledge. Empirical studies increasingly rely on neuroimaging methods, including fMRI. Neurofinance research focuses on utility, choices, preferences, loss aversion, financial risk, intertemporal choices and decision-making processes in social contexts. The growing number of neurofinance research articles in peer-reviewed journals testifies to the significance of this emerging field. The volume of neuroeconomic studies focusing on decision-making processes continues to increase steadily (Glimcher et al., 2009).

Utility is a fundamental concept in economics and financial research. In recent years, neuroeconomic research has increasingly focused on investor behavior. Frydman, Barberis, Camerer, Bossaerts and Rangel (2012) relied on fMRI to evaluate the assumptions of utility. These authors searched for neural evidence to prove or disprove the realization utility theory. They performed an experiment on a group of 28 volunteers who were asked to trade stock A, stock B, and stock C in an experimental market while their brain activity was monitored with the use of fMRI. The experiment was based on three assumptions. Firstly, it was assumed that activity in the ventromedial prefrontal complex (vmPFC), which encodes the value of options during choices, should be positively correlated with the capital gains or losses associated with stock trading. Secondly, the strength of the tested individuals' tendency to exhibit a disposition effect should be correlated with the strength of the realization utility signal in the vmPFC. Thirdly, it was assumed that realizing a capital gain generates a positive burst of utility, whereas realizing a capital loss generates a negative burst. Therefore, realizing a capital gain should increase activity in the ventral striatum (vSt), the reward center of the brain, whereas realizing a capital loss should decrease vSt activity. The results of fMRI examinations confirmed all three assumptions. According to the authors, neuroimaging provides strong evidence for the mechanisms underpinning the realization utility model. The experiment demonstrated that the realization of a capital gain was strongly correlated with increased activity in the vmPFC.

In turn, the realization of a capital loss was not significantly correlated with vmPFC activity. The activity of the vST was positively correlated with the realization of a capital gain, which confirmed the third assumption. Therefore, fMRI measurements contributed empirical evidence proving that investors derive utility from realizing capital gains. The influence of loss realization on reward cues in the brain was not validated due to a strong disposition effect. In each tested subject, an average of three losses was realized per scanning block; therefore, the results did not have sufficient statistical power to draw conclusions. According to the cited authors, this was the first study to demonstrate that neuroeconomics can substantially contribute to the validation of mathematical and economic models (Frydman et al., 2012).

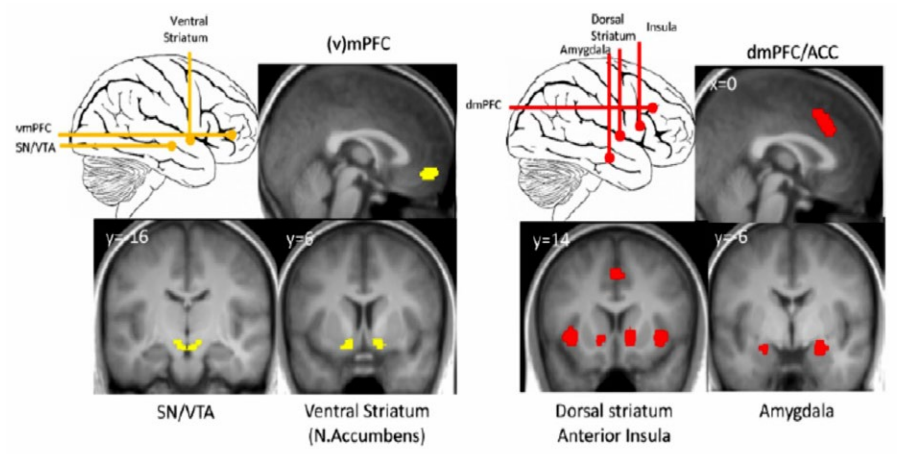
Neurofinance research also explores investor motivation and the mechanisms associated with investor behavior. In a study evaluating risk propensity, the posterior insula was activated when the tested subjects chose safe investment options, which indicates that this area of the brain is responsible for risk aversion. The nucleus accumbens, which plays an important role in processing and reinforcing reward stimuli, was activated when the subjects made more risky investment decisions (Maciejasz-Świątkiewicz & Musiał, 2014). Functional MRI scans demonstrated that realizing a capital gain increased the activity of the right hemisphere, whereas realizing a loss activated the left hemisphere of the brain. In turn, cash payments triggered the prefrontal cortex which is a part of the brain's reward system. The brain perceives money as a valuable object or a source of pleasure which activates older receptors in the reinforcement system (Smith, 2013).

Functional MRI was also used to determine the influence of reward and punishment pathways in the brain on investor behavior (Yarkoni et al., 2011; Rorden et al., 2007). Desirable actions are reinforced, and undesirable actions are suppressed by different areas in the brain's reward system. This approach is referred to as the dual-system hypothesis. The interpretation of risk aversion plays an important role in this process. According to the expected utility hypothesis, avoidance of punishment is associated with a sense of relief that can be perceived as a reward. Similar learning mechanisms can be implemented by the brain to seek reward and avoid punishment. The most frequently identified structures in reward and risk processing are presented in Figure 3. The ventromedial prefrontal complex (vmPFC) and the substantia nigra/ventral tegmental area are shown on the left. The components of the dopaminergic system are frequently identified in reward processing, particularly for positive stimuli that trigger approach behavior. The anterior insula, the dorsomedial prefrontal cortex extending into anterior cingulate cortex (dmPFC/ACC), the dorsal striatum (specifically, the head of the caudate nucleus) and the amygdala, which are frequently identified as processing risks to which most organisms are averse, are shown on the right. The brain's ability to dynamically change its structure and function is referred to as neuroplasticity, which plays the key role in learning. Humans learn to select behaviors for which they will be rewarded and avoid behaviors for which they will be punished.

Figure 3. Most frequently identified structures in reward and risk processing.

Left: "The ventromedial prefrontal cortex (vmPFC) and substantia nigra/ventral tegmental area, all part of the dopaminergic system, are frequently identified in reward processing, in particular for positive stimuli that trigger approach behavior. Anatomical mask is based on automated meta-analysis of fMRI studies with the term "reward" and anatomical mask of SN/VTA."

Right: "The anterior insula, the dorsomedial prefrontal cortex extending into anterior cingulate cortex (dmPFC/ACC), the dorsal striatum (specifically, the head of the caudate nucleus), and the amygdala are frequently identified as processing risk, which most organisms are aversive to. Anatomical mask is based on automated meta-analysis of fMRI studies with the term «risk». Clusters were thresholded at Z = 4, Gaussian filtered at FWHM = 5 with bspmview (Robert Spunt), and displayed with MRIcron".



Source: Rorden et al., 2007, pp. 1081–1088; Miendlarzewska et al., 2019, pp. 196–222.

Neurobanking is yet another field of study in neurofinance research which aims to identify factors that influence the financial decisions made by actors in the banking system and classify the benefits and risks associated with banking and financial transactions. Therefore, the main objective of neurobanking studies is to analyze the motivation and operations of private and institutional investors in contemporary banking and financial markets (Flejterski, 2009). Knutson et al. relied on fMRI to identify distinct neural circuits associated with consumers' purchasing decisions. The participants were scanned while engaging in a novel *Save Holdings or*

Purchase (SHOP) procedure. The study demonstrated that product preference activated the nucleus accumbens, a structure in the center of the brain which processes specific information about the availability and value of rewards. The prefrontal cortex, a region of the brain located near the cerebral peduncle and responsible for higher cognitive functions, including decision-making, was activated when the price of the product was displayed. The cited study confirmed the hypothesis that the brain recognizes its own preferences as a potential reward and regards price as a cost. At the neuronal level, a purchasing decision is driven by the belief that anticipated gain will outweigh anticipated loss, which suggests that these decisions are more emotional than rational in nature. According to Knutson, neuroeconomic analyses are also helpful in explaining consumers' decisions to pay with cash or card. Risk-averse strategies activated the posterior insula, whereas the choice of risky strategies led to tension between different and competing brain structures. The results of neuroimaging studies indicate that the nucleus accumbens is activated in anticipation of gain, whereas the anterior portion of the insula is involved in loss prediction (Shermer, 2009).

Neurofinance is a relatively new field of study, which is why the existing analyses are largely fragmentary and fail to describe the financial market in a synthetic, comprehensive manner. In addition, most behavioral finance and neurofinance researchers analyze market phenomena *ex post*, whereas very few attempts have been made to model market processes *ex ante* (Czerwonka et al., 2014). According to the literature on economic history and methodology, simplified models based on exclusively rational behavior (*homo economicus*) will be replaced by neurofinance-based behavioral models in the near future (Bruni & Sugden, 2007). This observation implies significant methodological changes that will lead to a clear distinction between normative and descriptive theories (Colander, 2000). The normative approach will focus on rational behavior that is associated with the idealistic *homo economicus* concept, whereas descriptive theories will analyze real-world consumer choices. This reorientation would contribute to an improvement in the methodology of economic and finance research (Wojtyna, 2008).

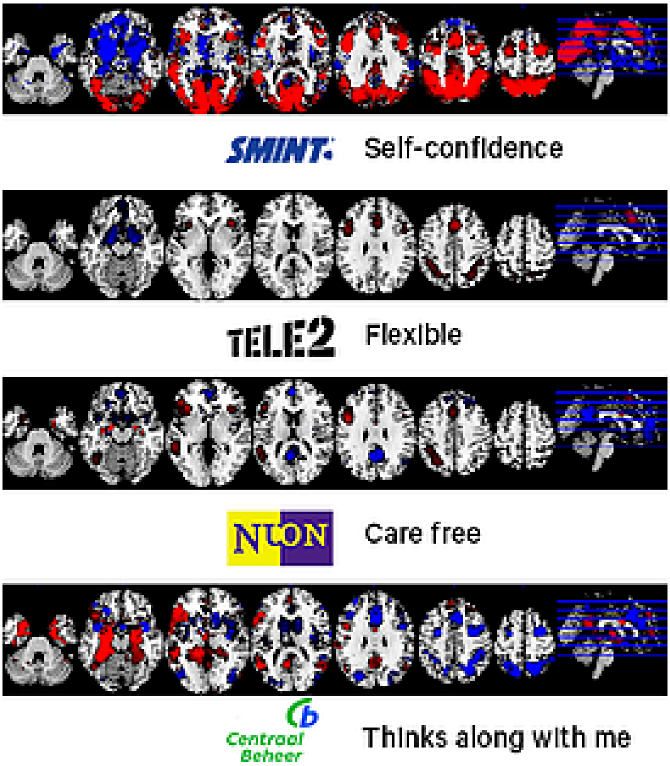
An interdisciplinary approach is also applied in contemporary neuroaccounting research, which aims to identify reactions that occur at the neuronal level and generate observable economic behaviors. Neuroaccounting has emerged from experimental trends in behavioral accounting, and it combines neuroeconomics, neurobiology and neurochemistry. The emerging discipline focuses on human behavior and neurophysiological processes in the brain. Behavioral accounting acts as a link between classical accounting theory and modern neuroaccounting. The search for the causes of decision-makers' behavior in psychological theories has spurred the development of behavioral economics, including behavioral finance and behavioral accounting, which syncretizes classical economic theory with descriptive psychological models (Camerer et al., 2004). Many psychological processes are automatic and occur at the subconscious level, which is why traditional research methods based on an analysis of the states of mind communicated by the subjects are insufficient. These limitations have prompted the development of neuroeconomics research. In accounting, fMRI has been used to evaluate the links between the brain, human behavior, accounting, and financial markets. Barton, Berns, and Brooks (2014) used fMRI to study neuronal activity in 35 adult investors learning the earnings per share disclosed by 60 publicly traded companies. The study provided strong neurobiological evidence for an asymmetric reaction to positive and negative earning news, which is consistent with Kahneman and Tversky's (1979) prospect theory in behavioral accounting. Farrell, Goh, and White (2014) relied on fMRI scans of brain activity to study how fixed wage contracts and performance-based financial incentives influence the decisions made by managers. They studied the role played by two information processing systems in the brain – System 1 processing, which relies on affect and intuition, and System 2 processing, which relies more on logic and evidence in reasoning and behavior. The study revealed that unlike fixed-wage contracts, performance-based contracts induced more analytical processing, thus minimizing the risk of affective reactions that are potentially costly to the company. Functional MRI can promote a deeper multidisciplinary understanding of financial and accounting phenomena. Therefore, neuroaccounting has immense developmental potential.

Economic studies based on fMRI have enabled researchers to identify the key areas of the brain responsible for specific behaviors. The obtained results indicate that the ventral striatum is associated with the reward system, the orbitofrontal cortex modulates desire, the medial prefrontal cortex is responsible for positive social responses, the posterior cingulate cortex is involved in conflict, whereas the amygdala controls threat and fear-based behaviors in humans.

Applicability of magnetic resonance in neuromanagement and neuromarketing

Knowledge of neuroanatomy and neurophysiology can be practically used in contemporary neuromanagement. Marketing management is a scientific discipline that studies the selection of target markets, customer acquisition and maintenance through value creation, and communicating value to customers (Kotler & Keller, 2013). Contemporary marketing management focuses on satisfying customer needs and desires while maximizing customer satisfaction and fulfilling expectations relating to the purchased products. To satisfy customer needs, marketing managers have to understand the "mind of the market," namely the dynamic mutual interactions between the cognitive processes of consumers and marketing experts (Wąsikowska, 2015). The aim of neuromarketing is to analyze and explain consumers' subconscious cognitive processes in response to specific marketing stimuli. Functional MRI enables accurate evaluations of emotional responses at the cellular level, from recognition and approval to gratification, by monitoring the flow of oxygenated blood in specific regions of the brain in response to different marketing stimuli. A better understanding of consumer preferences, expectations, and motivations, on top of better predictions of consumer behaviors can contribute to the implementation of more effective marketing strategies. For this reason, modern tools are increasingly applied to study customers' purchasing preferences. Functional MRI is applied in neuromarketing research to anticipate consumer behaviors, identify the key determinants of decision-making processes, and measure customers' conscious and subconscious responses, emotions and experiences. Neuroimaging enables researchers to examine the activity of different brain regions and identify cerebral structures that are directly responsible for cognitive and emotional processes. Functional MRI is most often used to measure brain activation in response to advertising (evaluations of subconscious emotions and responses activated by advertising optimize advertising costs and broadcast time), test marketing concepts (evaluations of consumer perceptions maximize ROI already before the advertisement is broadcast and support predictions of the effectiveness of the final edited version of an advertisement), evaluate neurobranding (neural activity associated with a given brand is analyzed to directly test the influence of marketing communication on brand associations in the customer's brain) and evaluate neuropackaging (analyses of the influence of packaging design on consumers' purchase intentions; analyses of the correlations between packaging design, purchase intentions and subconscious esthetic impressions enable companies to design attractive and unique custom packaging). The British company Neurosense has conducted pioneering research on the application of fMRI for marketing purposes. The use of fMRI techniques for neurobranding and the recording of consumers' fast, intuitive, and subconscious associations with a given brand is presented in Figure 4. Brand associations induce neural activity in different regions of the brain.

Figure 4. Application of fMRI in neurobranding.



Source: Neurensics, https://www.neurensics.com/en/neurobranding?hsLang=en (access: 05.05.2022).

Four types of neuromarketing research methods are generally identified in the literature: neuroimaging (which directly measures brain activity), biometry (which measures brain activity, heart and respiratory rate, and analyzes changes in posture and facial expression in response to new, significant or motivating stimuli), oculography (which measures eye movements) and psychometrics (which measures response times that reflect subconscious associations and attitudes). Neurophysiological measurements overcome some of the limitations of conventional measurements in marketing research. Neuroimaging techniques are deployed to analyze consumer responses to marketing stimuli, diagnose brain activity, and register perception activities associated with the senses of vision, olfaction, and touch. Neuromarketing is a dynamically growing field of study that relies on fMRI methods to register and analyze changes in the activity of different brain regions in subjects who perform specific tasks during exposure to advertising. The quality of measuring equipment and the MRI scanner plays a significant role in neuroimaging. The equipment used for research purposes should be characterized by high spatial, contrast, and temporal resolution. Temporal resolution in the millisecond range is required to visualize changes in brain activity associated with processing visual and acoustic stimuli in response to television advertisements (Venkatraman et al., 2014). Functional MRI techniques are used to test consumer responses to advertising by measuring changes in the activity of the prefrontal cortex, amygdala, and hippocampus.

In a marketing study conducted by McClure et al. (2004), fMRI was used to analyze subjective consumer preferences for Coca-Cola and Pepsi. The authors investigated neural responses to product brands and differences in neural activity during anonymous and brand-cued delivery of Coke and Pepsi. The subjects were asked to describe their taste and brand preferences before the experiment. A behavioral taste test was conducted inside an fMRI scanner. The subjects were positioned inside the scanner tube, and instructed to watch images of Pepsi or Coca-Cola cans, or unlabeled cans, while swallowing the administered beverages. Pepsi and Cola were delivered to the subjects through specially designed plastic tubes. The study generated surprising results. Brand knowledge (a Pepsi can or a Cola can was displayed on the screen) activated the hippocampus, a region of the brain associated with memory. In contrast, the absence of brand knowledge (anonymous delivery of Pepsi or Cola) recruited the gustatory cortex, which is responsible for the perception of taste and flavor. In addition, the subjects' prior affective bias was altered when brand information was not available.

Another neuromarketing study was conducted by the INSEAD research team headed by Plassmann. A neuroimaging analysis of brain structures was performed in subjects who tasted three differently priced wine brands. The study revealed that the tested subjects perceived the analyzed brands differently and preferred the most expensive wine. In reality, the tasted wines were identical. Neuromarketing studies have also explored the biological underpinnings of the concept of ownership. Research involving fMRI methods fills a gap in the existing knowledge in traditional psychology which is based on observations of human behavior (Clithero & Smith, 2009). De Martino et al. relied on fMRI to analyze the involvement of different brain regions in subjective value coding and individual preferences that influence perceptions of value and decision making.

Discussion and research limitations

This article focuses on the interdisciplinary research approach and the growing tendency to use medical diagnostic methods in economic research. Magnetic resonance is a neuroimaging technique that offers considerable benefits for medical and research purposes. Unlike X-ray, computed tomography (CT) or PET examinations, the subject is not exposed to ionizing radiation, which is particularly important when medical exams, clinical trials or experiments have to be repeated. During MRI, the brain can be scanned in any plane (coronal, sagittal, axial) and the resulting images are characterized by superior resolution. Magnetic resonance imaging also supports multi-phase, dynamic and functional examinations of brain activity, and these modalities play a key role in evaluations of the functional areas of the cerebral cortex.

Nothwithstanding these advantages, MRI remains the most expensive neuroimaging method. The high costs are mainly associated with the use of an MR scanner and other equipment. Examination time is relatively long, and data acquisition and image (scan) analysis are labor-intensive processes. Magnetic resonance imaging requires a strict preparation and scanning protocol, which limits the applicability of this diagnostic technique. Research studies involving fMRI require substantial funding as well as access to diagnostic equipment, which is possible only in highly specialized, interdisciplinary research centers. The associated costs, the prolonged examination protocols, on top of high equipment and personnel requirements (including electroradiology technicians and physicians) are the main limitations of MRI as a tool in economic research.

In conventional MRI, the interactions between hydrogen atoms in water molecules in the human body and the strong electromagnetic radiation generated by the MRI scanner are interpreted and visualized. In fMRI, brain scans are additionally influenced by blood flow and oxygen levels in active regions of the cerebral cortex. Increased neuronal activity raises oxygen consumption and the demand for oxygen. As a result, blood flow intensifies in the examined region. Oxygen is delivered to tissues via oxyhemoglobin, which is formed when oxygen binds to hemoglobin in erythrocytes (red blood cells). Functional MRI is based on the assumption that active brain regions require more oxygen to support metabolic processes, which can be assessed by an analysis of blood flow (hemoglobin levels) in the brain. These assumptions are the fundamental tenets of neuroimaging in neuroeconomics research and neuromarketing.The increase in cognitive realism made possible by objective neuroimaging methods such as fMRI allows for a more accurate understanding, description and prediction of market phenomena or purchasing behavior. However, the specific nature of MRI and fMRI, and their application in economics, management, and marketing raises certain ethical reservations. Magnetic resonance imaging involves a very strong magnetic field, and only individuals meeting strict safety criteria may be qualified to participate in such study. It is worth considering whether it is reasonable and ethical to study consumers' brains to identify the determinants of the purchasing process. Is it morally acceptable to scan the brain to uncover the variables that influence decision-making and purchasing behavior? To what extent can the development of modern neuroimaging technologies be used for commercial purposes? These and similar questions remain open. According to the author, the use of advanced methods of brain imaging must be accompanied by rigorous adherence to ethical research standards. Despite the high precision, accuracy and reliability of the obtained neuroimaging results, some ethical concerns regarding the use of MRI and fMRI in economics, management and marketing persist. This article is only an outline of the issues.

Summary

An analysis of the history of economic thought and the methodologies employed in classical economic research indicates that traditional economic theories are largely grounded in observable human behavior. This reliance stemmed from the absence of technological solutions for direct measuring and validating human behaviors, motivations, responses and emotions. In this context, Samuelson's revealed preference theory, which postulates that unobservable consumer preferences can be inferred from their purchasing habits, holds particular significance.. Subsequent economic theories that emerged as the dominant trends in empirical research gave rise to "as-if" behavioral economics.Although many of these theories were cohesive and mathematically sophisticated, they often failed to stand up to empirical testing because they assumed that market actors behaved in a rational manner. New solutions promoting the "as-is" perspective in economic research are currently being sought to overcome these cognitive limitations. These emerging scientific paradigms aim to provide more accurate descriptions of the analyzed phenomena and more reliable predictions of economic processes on the market.

Neuroeconomics is a rapidly evolving field of study that investigates neural correlates of subjective value and economic decision-making, offering immense theoretical and practical potential. Neuroeconomics is a subfield of behavioral economics, which relies on strictly defined research tools and methodology. Modern brain imaging methods are used

to examine the course and outcome of decision-making processes, and they substantially contribute to progress in neuroeconomics. Neuroeconomic studies are conducted to map and measure brain activity during specific tasks and cognitive processes. Electrophysiological and hemodynamic techniques belong to the group of modern diagnostic methods that account for the biological underpinnings of brain function. Electrophysiological methods include electroencephalography (EEG), magnetoencephalography (MEG) and transcranial magnetic stimulation (TMS), while hemodynamic methods involve positron emission tomography (PET) and fMRI. Knowledge of the methodology of economics and the methods of imaging neuroeconomics forms the basis of scientific inference.

Despite the potential advantages of modern diagnostic methods in economic studies, researchers have also voiced their concerns regarding further development of economic sciences. Some scientists question the significance of interdisciplinary research teams and the exploration of trends in neuroscience within economics. Do scientific approaches that combine economic theory with advances in medicine, neurology, biology, and biochemistry contribute to the unity of science, or are they mererly fashionable trends that reflect our fascination with cutting-edge research tools? Is neuroeconomics truly an important and promising field of study with theoretical and practical implications? These questions lie at the heart of an ongoing debate between opponents and enthusiasts of neuroeconomics on the future directions of economic research. The relevance of neurological explanations for behavior in economics has been challenged by Gul and Pesendorfer (2005) who argued that neurological data cannot refute economic theories and therefore neuroeconomics is not a methodologically justified field of study. Similar criticism was expressed by Harrison (2008) who posited that neuroeconomics can do more harm than good because neuroscientific methods may blur the line between scientific knowledge in economics and just compelling story-telling. Some scientists have criticized the fascination with neuroscience in general, without making a direct reference to its application in economics or finance (Satel & Lilienfeld, 2013). However, proponents of neuroeconomics – including McCabe, Camerer, Zak, and Glimcher – argue that neuroeconomics enables scientists to validate the existing economic theories and adopt a completely new approach to describing economic reality. Neuroimaging techniques have particularly contributed to the development of neuromarketing which is a less controversial field of study than neuroeconomics or neurofinance and where economic theories can be rapidly tested in practice (Walczak, 2014).

Nonetheless, empirical evidence gathered by neuroeconomics research can significantly contribute to the development and scientific credibility of modern economics. Magnetic resonance imaging and fMRI methods are used in economic research to account for the effects of neuroimaging in the process of developing economic decision-making support systems. Therefore, the application of diverse research approaches and methods appears justified in efforts to identify the factors and determinants that drive the economic decisions of market participants. The search for new applications of neuroscience, along with reliable neuroimaging data, creates numerous opportunities for implementing scientific assumptions and theories in practice. Neuroeconomics research can substantially expand the existing knowledge about human behavior in economic space.

Economics is the study of how individuals and societies allocate scarce resources, which is why decision-making is central to economic theory. Neuroeconomics investigates neuro-microeconomic problems associated with the behavior of individual market participants, as well as neuro-macroeconomic issues involving entire societies (Noga, 2017). Research on decision-making processes is conducted both in strictly economic contexts and within broader social frameworks. Neuroscience and methods enabling direct acquisition of neural signals from the human brain and generation of images of neuronal activity during cognitive tasks provides the most sophisticated tools for improving the reliability of collected data. The biological underpinnings of human behavior constitute the main research problem in neuroscience. Modern neuroimaging methods are applied mainly in neurofinance and neuromarketing to study consumers' buying preferences. Cognitive neuroscience and neuroeconomics research expand our understanding of decision-making processes and contribute to the development of more effective economic decision-making support systems. Magnetic resonance imaging can improve the reliability of results in economic research. Neuroimaging thus serves as a useful tool in business practice by offering reliable data for modeling decision-making processes.

Advanced neuroimaging techniques can be used to forecast economic events by analyzing the decisions made by individuals and groups. In an era of globalization and rapid socioeconomic transformation, efforts to construct economic growth scenarios and anticipate market events are particularly relevant. A holistic, interdisciplinary approach to analyzing economic processes promotes the development of economics as a science and the implementation of effective solutions in economic practice. Therefore, the cognitive and practical implications of neuroimaging constitute valuable premises for advancing research in economics with the use of modern neuroimaging methods. Harmonious and sustainable economic development requires novel, creative and innovative research methods that are adequate for analyzing the existing and potential future socioeconomic challenges. In conclusion, research methods in economics must also adapt to the changing methodological paradigm. An interdisciplinary science approach is therefore crucial to understanding how the market works.

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