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A Comprehensive Bibliometric Analysis of fNIRS and fMRI Technology in Neuromarketing

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Abstract: The aim of this study is to perform a comprehensive bibliometric analysis of functional near-infrared spectroscopy (fNIRS) and functional magnetic resonance imaging (fMRI) tools. To achieve this aim, we adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol and bibliometric analysis (VOSviewer) for extracting the relevant papers (articles and reviews) from the Scopus database between 2002 and 2022. A total of 86 papers were included in the analysis. The results showed an increasing trend in publications over the years—the top countries in terms of publication outcome were the United States, Germany, Spain, and Australia. The analysis also identified the most influential authors and institutions in the field. In addition, we analyzed the most frequently cited articles, journals, and keywords related to fNIRS and fMRI tools. This bibliometric analysis provides insights into the current state of research on fNIRS and fMRI tools. It also provides insights into the direction of future research in this field. In this study, we will provide general insights and details about current trends in neuromarketing research using fNIRS and fMRI.

Keywords: fNIRS; fMRI; bibliometric analysis; neuromarketing; consumer neuroscience; Scopus database.

JEL classification: M30; M31; M39; O3.

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1. INTRODUCTION

The field of neuromarketing has gained significant attention in recent years due to its potential to reveal the underlying mechanisms of consumer behavior (Pilelienė *et al.*, 2022; Alsharif *et al.*, 2023a). Neuromarketing is a hybrid field that includes marketing, neuroscience, and psychology (Alsharif *et al.*, 2021a), which relies on advanced technologies such as functional near-infrared spectroscopy (fNIRS) and functional magnetic resonance imaging (fMRI) to measure participants' neural activity as they engage with different marketing stimuli (Cherubino *et al.*, 2019; Alvino *et al.*, 2020; Alsharif *et al.*, 2022a; Alsharif *et al.*, 2022b). These non-invasive tools provide researchers with valuable insights into how consumers respond to various marketing tactics, such as advertisements, product packaging, and brand logos (Ernst *et al.*, 2013; Jackson & Kennedy, 2013). Thus, scholars have shifted to using neuroscience tools such as but not limited to fMRI to measure and record subconscious and unconscious consumer responses toward marketing stimuli, which cannot be measured by self-report methods such as but not limited to surveys (Cherubino *et al.*, 2019; Alsharif *et al.*, 2021b).

fNIRS is a non-invasive neuroimaging technique that measures changes in blood oxygenation in the brain as an indirect measure of neural activity (Nambu *et al.*, 2009; Gier *et al.*, 2020; Sargent *et al.*, 2020). It emits near-infrared light into the brain tissue and detects the reflected light using specialized sensors (Kopton & Kenning, 2014; Çakir *et al.*, 2018; Krampe *et al.*, 2018; Burns *et al.*, 2019). The amount of reflected light indicates the level of oxygenated and deoxygenated blood in the brain, reflecting the neurons' activity in that region. fNIRS has several advantages over other neuroimaging techniques, including its portability, ease of use, and lower cost (Çakir *et al.*, 2018; Krampe *et al.*, 2018; Alvino *et al.*, 2020; Alsharif *et al.*, 2021d). It is particularly useful in studying brain activity in naturalistic settings, such as when participants are watching television commercials or shopping in a retail store (Gier *et al.*, 2020; Sargent *et al.*, 2020). fMRI is a neuroimaging technique that uses powerful magnets to measure changes in blood flow in the brain, which indicates changes in neural activity (Linzmajer *et al.*, 2021; Sánchez-Fernández & Casado-Aranda, 2021). Unlike fNIRS, fMRI provides a more detailed spatial resolution, allowing researchers to identify the precise location of brain activity (Lloyd-Fox *et al.*, 2010; Burle *et al.*, 2015; Krampe *et al.*, 2018). However, fMRI is more expensive and requires participants to remain confined, making it less suitable for naturalistic settings (Alsharif *et al.*, 2020b). Nonetheless, fMRI is widely used in neuromarketing research to investigate how consumers respond to different marketing stimuli (Alsharif *et al.*, 2022c).

fMRI and fNIRS are two neuroimaging methods that are used to measure levels of oxygenated and deoxygenated hemoglobin in a non-invasive and metabolically interesting way (Shimokawa *et al.*, 2009; Ernst *et al.*, 2013; Jackson & Kennedy, 2013; Alvino *et al.*, 2020). While fMRI provides greater spatial accuracy, estimated at 1-10 mm3 in deep brain structures, fNIRS has poor spatial accuracy, estimated at 4cm in cortical activity regions (Lloyd-Fox *et al.*, 2010; Burle *et al.*, 2015; Krampe *et al.*, 2018). However, both methods have acceptable temporal accuracy, estimated in seconds (Sitaram *et al.*, 2009; Kopton & Kenning, 2014). Researchers have employed fMRI and fNIRS in marketing studies to record neural responses associated with consumer behavior, such as preference, perception, purchase decisions, and choices (Lloyd-Fox *et al.*, 2010; Kopton & Kenning, 2014). Additionally, fNIRS is a portable, innovative, and cost-effective neuroimaging method compared to fMRI (Plichta *et al.*, 2011; Ernst *et al.*, 2013; Kopton & Kenning, 2014; Çakir *et al.*, 2018; Krampe *et al.*, 2018).

Aware of the growing interest in neuromarketing, several studies analyzing scientific production on neuromarketing have already been published (Alsharif *et al.*, 2021d; Alsharif *et al.*, 2023b; Alsharif *et al.*, 2023c). However, no previous research was performed to map the ((neuromarketing OR consumer neuroscience) AND (functional near-infrared spectroscopy OR fnirs) OR (*magnetic resonance imaging OR *mri)) research production in the Scopus database. Therefore, this study differs from other review papers concentrating on the global academic research trends of studies that used fNIRS and fMRI tools in neuromarketing or consumer neuroscience research between 2002 and 2022 on the Scopus database. To this end, this study tries to fill the gap in scientific literature. This study aims to provide a comprehensive bibliometric analysis of the ((neuromarketing OR consumer neuroscience) AND (functional near-infrared spectroscopy OR fnirs) OR (*magnetic resonance imaging OR *mri)) identifying the most prolific countries, academic institutions, authors, journals. In addition, the articles having the highest numbers of citations, the co-citation network of authors and papers, and the hot keywords with occurrences will be determined. The main contributions and steps of this bibliometric analysis study are summarized and listed as follows:

(1) To identify the growth of annual scientific publications based on journals' outputs.

(2) To identify the overall performance, such as productive countries, institutions, journals, and authors.

(3) To identify the most prominent themes/keywords in the ((neuromarketing OR consumer neuroscience) AND (functional near-infrared spectroscopy OR fnirs) OR (*magnetic resonance imaging OR *mri)).

(4) To identify the most-cited articles to be considered in future studies.

(5) To provide new references and directions to the scholars who are interested in the ((neuromarketing OR consumer neuroscience) AND (functional near-infrared spectroscopy OR fnirs) OR (*magnetic resonance imaging OR *mri)).

The structure of this research is as follows: Section 2 outlines the methodology employed in this study. Section 3 is concerned with a bibliometric analysis of pertinent literature. Section 4 discusses the results of the paper. Section 5 provides concise conclusions. Finally, Section 6 presents the study's limitations and potential future directions.

2. METHODS

The research used the PRISMA protocol to find relevant papers and conducted a bibliometric analysis to determine global research trends in neuromarketing. The study looked at the most productive countries and academic institutions, leading journals in the field, prolific authors who published papers using fMRI and fNIRS tools, most-cited papers, and occurrences of keywords to assess improvements in publications. This study aims to provide an overview of the current trends to fill the existing gap. Accordingly, four research questions were established to justify the structure and to gain the full view of the existing scientific research in the analyzed domain:

RQ_1: Is there and what is the annual growth of scientific publications in the field?

RQ_2: What are the most productive a) countries; b) academic institutions; c) journals; d) authors?

RQ_3: What are the most prominent keywords in selected articles?

RQ_4: What are the most-cited articles in the field?

Endeavoring to answer the research questions, the current study starts by extracting articles from the Scopus database in March 2023. In addition, this study has followed the instruction Alsharif *et al.* (2020a) to present a thorough bibliometric analysis detecting and listing the most productive countries, academic institutions, journals, and authors; later on, a brief description of each analyzed parameter is provided. The VOSviewer software was utilized to create visualization maps, which simplifies bibliometric research across various fields, including neuromarketing (Alsharif *et al.*, 2022a; Pilelienė *et al.*, 2022; Alsharif *et al.*, 2023b). In particular, VOSviewer has been used in several studies related to neuromarketing (see Alsharif *et al.*, 2021c; Alsharif *et al.*, 2022d) to gain a comprehensive understanding of the development of using fNIRS and fMRI in this field. The procedure used in the study enabled the identification of 86 papers that were published between 2002 and 2022. The study's authors focused specifically on papers, including articles and reviews, that utilized fNIRS and fMRI tools between 2002 and 2022 due to the significant increase in publications. Additionally, only papers written in English were included, as it was the most typically used language in the field. The study aimed to identify as many relevant papers as possible to explore and analyze the global academic trends (e.g., productive countries, institutions, authors, and other relevant factors) related to using fNIRS and fMRI in marketing activities. The selection process for selecting articles is shown in Figure no. 1, and the articles included in the study had to meet the following traits:

- Methods: fNIRS and fMRI.
- Publication year: 2002-2022.
- Language: English.
- Document type: article and review (conference papers (11 papers), book chapters (8), short survey (2), Books (1), Notes (1), and editorials (1) had been excluded).

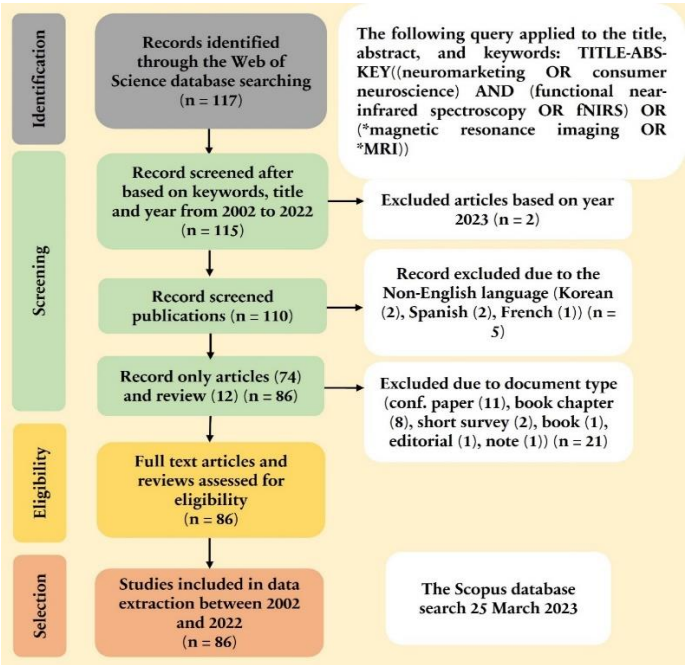

Figure no. 1 – PRISMA process for selecting papers

3. RESULTS

As a result of the procedure, 86 academic journal papers that utilized fNIRS and fMRI tools in marketing research were identified. The analysis revealed a significant publication growth, with over 50% of the total papers being published in the last five years, from 2018 to 2022. Figure no. 2 illustrates the annual publications published between 2002 and 2022, with one paper being published in 2002 and the number increasing almost seventeen-fold in 2020 before slightly decreasing to eight times in 2022. The increasing interest among researchers and practitioners in neuromarketing has led to a rise in the number of publications and researchers interested in using fNIRS and fMRI in marketing research.

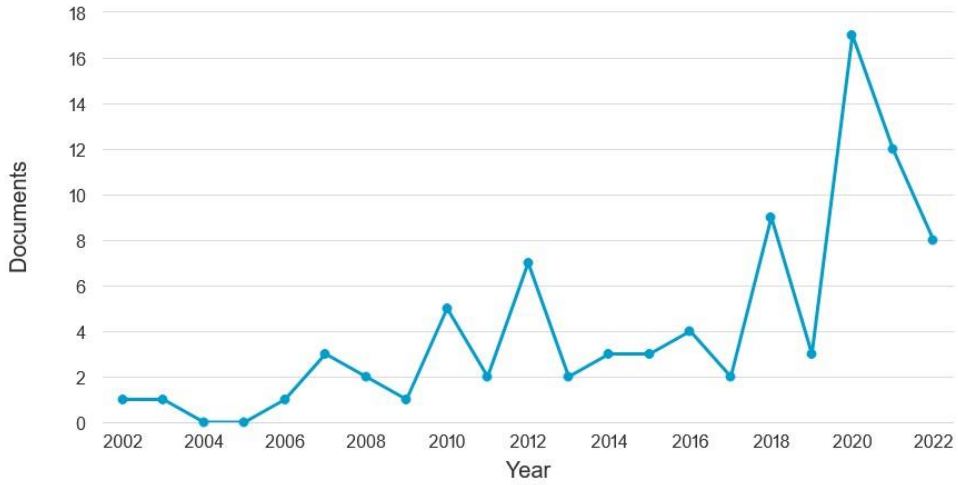

Figure no. 2 – The annual papers used fNIRS and fMRI from 2002 to 2022.

3.1 A bibliometric analysis

3.1.1 Leading countries and institutions

The analysis revealed that the countries that produced at least three papers could be classified into three groups based on their productivity levels. The first group consists of one country that produced more than twenty papers, the second group consists of one country that published between ten and twenty papers, and the third group consists of eleven countries that produced between three and ten papers each. As depicted in Table no. 1, the USA, Germany, and Spain have collectively contributed to more than half of the total papers since 2002. Specifically, the USA has been the most productive country, with twenty-five papers and the highest total citation count (1455 TCs). The University of Southern California, an institution in the USA, has published five papers with 471 total citations of the institution (TCsI). While Denmark has published four papers with 470 TCs, the Copenhagen Business School, the Danish institution, has published the second-highest-cited papers with 428 TCsI. Although at the bottom of the list, Mexico has contributed to the fifth-highest-cited papers with 220 TCs, and its institution, Tecnologico de Monterrey, has published two papers with the fifth-highest-cited papers (179 TCsI).

Table no. 1 – The most productive countries and academic institutions of neuromarketing research (minimum of three articles contribution of the country)

Country	TPs by the end of 2022	TCs by the end of 2022	The most prolific academic institutions	TPsI by the end of 2022	TCsI by the end of 2022
USA	25	1455	University of Southern California	5	471
Germany	15	674	Heinrich-Heine-Universität Düsseldorf	6	183
Spain	7	17	Universidad de Granada	4	5
Australia	6	131	Swinburne University of Technology	2	81
Canada	5	251	Université McGill	3	193
Austria	5	60	Wirtschaftsuniversität Wien	1	16
Italy	5	45	Sapienza Università di Roma	3	41
Netherlands	5	128	Erasmus Universiteit Rotterdam	3	121
Denmark	4	470	Copenhagen Business School	2	428
Japan	4	33	Tohoku University	2	24
China	4	10	Zhejiang University	2	8
South Korea	3	72	Sungkyunkwan University	2	24
Mexico	3	220	Tecnologico de Monterrey	2	179

Note: TPs; total publications, TCs; total citations, TPsI; total publications by institution, TCsI; total citation of the institution

3.1.2 Most productive authors

Table no. 2 displays the most prolific authors in neuromarketing research with the highest number of papers. Nine authors from seven different countries and nine different academic institutions were identified. Two authors have produced six papers each, two authors have published four papers each, and the rest of the authors have released three papers. Reimann, M. and Kenning, P. are the most productive authors, with six papers each and affiliations with Eller College of Management (USA) and Heinrich-Heine-Universität Düsseldorf (Germany) with 468 and 266 total citations (TCs), respectively. Krampe, C. and Casado-Aranda, L.A. have consecutively produced four papers each, with 65 and 5 TCs. The remaining authors have published three papers each. For more details, check Table no. 2.

Table no. 2 – The most-productive authors with a minimum of three papers

Author's name	TPs by the end of 2022	TCs by the end of 2022	Affiliation of the author	Country
Reimann, M.	6	468	Eller College of Management	USA
Kenning, P.	6	266	Heinrich-Heine-Universität Düsseldorf	Germany
Krampe, C.	4	65	Wageningen University & Research	Netherland
Casado-Aranda, L.A.	4	5	Universidad a Distancia de Madrid	Spain
Zaichkowsky, J.	3	460	Beedie School of Business	Canada
Smidts, A.	3	121	Erasmus Universiteit Rotterdam	Netherland

Author's name	TPs by the end of 2022	TCs by the end of 2022	Affiliation of the author	Country
Hubert, M.	3	76	Aarhus Universitet	Denmark
Babiloni, F.	3	40	Hangzhou Dianzi University	China
Sánchez-Fernández, J.	3	1	Universidad de Granada	Spain

3.1.3 Leading journals

Table no. 3 shows the journals that have published at least three papers that used fNIRS and fMRI tools in neuromarketing research. One journal has published five papers, one journal has published four papers, and the remaining journals have published three papers each. Frontiers in Human Neuroscience is the most productive journal with five papers, and published the third-highest-cited paper was written by Kopton and Kenning (2014) and used the fNIRS tool. The Journal Of Consumer Psychology, which has published three papers, has the highest-cited paper with 281 TCs written by Reimann *et al.* (2010) and used the fMRI tool. Qualitative Market Research, which is located at the end of the list with three papers, has the second-highest-cited paper with 88 TCs written by Kenning *et al.* (2007) and used the fMRI tool.

Table no. 3 – The most productive journals with a minimum of three published papers

Source/Journal	TPs by the end of 2022	TCs by the end of 2022	Reference of the most-cited paper by the end of 2022	Tool	TCs by the end of 2022	Publisher
Frontiers in Human Neuroscience	5	116	Kopton and Kenning (2014)	fNIRS	66	Frontiers Media Sa
European Journal of Marketing	4	101	Krampe *et al.* (2018)	fNIRS	37	Emerald Publishing
Frontiers in Neuroscience	3	9	Gier *et al.* (2020)	fNIRS	5	Frontiers Media Sa
Frontiers in Psychology	3	7	Cao and Reimann (2020)	fNIRS	3	Frontiers Media Sa
Journal of Consumer Psychology	3	476	Reimann *et al.* (2010)	fMRI	281	Wiley-Blackwell
Journal of Economic Psychology	3	98	Stallen *et al.* (2010)	fMRI	54	Elsevier
Journal of Marketing Research	3	120	Chen *et al.* (2015)	fMRI	49	American Marketing Association
Psychology and Marketing	3	26	Stillman *et al.* (2020)	fMRI	10	Wiley-Blackwell
Qualitative Market Research	3	119	Kenning *et al.* (2007)	fMRI	88	Emerald Publishing

3.1.4 Keywords analysis

In bibliometric analysis, keyword occurrences provide a quantitative approach to express the strength of links between paired keywords, with a larger number indicating a stronger link. This analysis provides a comprehensive explanation of the article's content. The link strength

between keywords reflects their frequency in the article, while the total number of links represents the overall number of keyword appearances in the article. The current paper conducted an author keywords co-occurrence analysis using VOSviewer software, which involved 35 keywords with at least two occurrences. This method is important for presenting general claims about the article's content and assessing trend themes in a particular subject, such as neuromarketing. The results showed that fMRI and fNIRS tools had been frequently used to study and understand consumer behaviors, including emotions and decision-making, toward marketing stimuli like advertising and branding. Figure no. 3 depicts these findings.

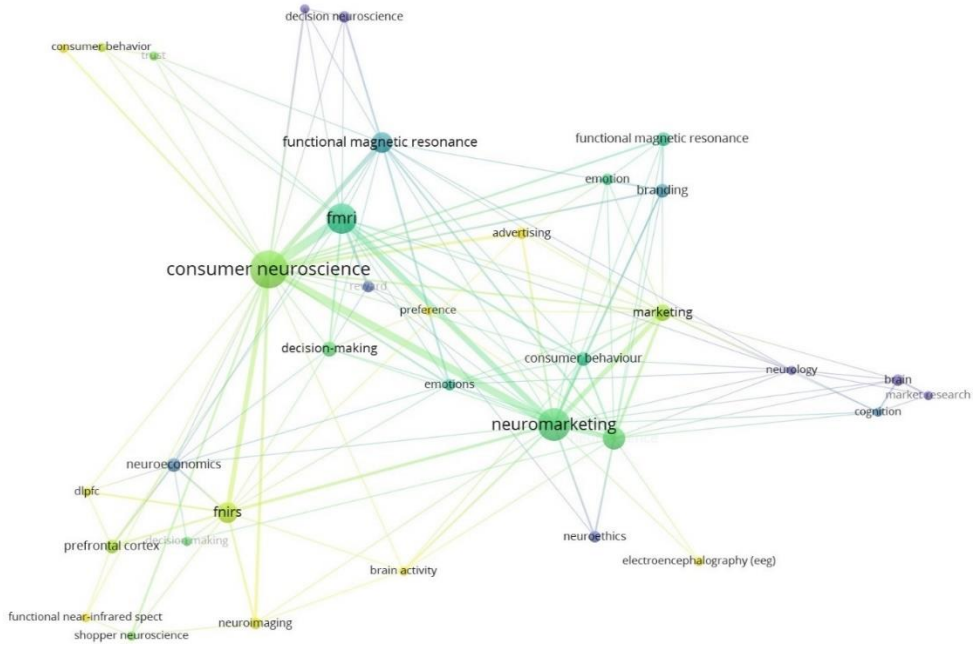

Figure no. 3 – Map of authors' keywords co-occurrence (with min. two occurrences)

Table no. 4 provides an overview of the most frequently used keywords that have appeared at least four times in the data. The term "consumer neuroscience" has the highest frequency with 31 instances and 37 total-link-strength, followed by the term "neuromarketing". Both of these fields have utilized functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIRS) techniques to investigate and comprehend consumer behavior, decision-making, and the prefrontal cortex's response to marketing stimuli such as branding. The term "consumer behavior" has been used four times with 12 total-link-strength, "decision-making" has been used five times with seven total-link-strength, and "prefrontal cortex" has been used four times with five total-link-strength. Similarly, the term "branding" has appeared four times with ten total-link-strength.

Table no. 4 – Top keywords by a minimum of four occurrences

#	Categories	Keyword	Occurrences	Total-link-strength
1	**Field**	Consumer neuroscience	31	37
		Neuromarketing	23	36
		Neuroscience	11	15
		Marketing	6	15
		Decision-making	5	7
		Consumer behavior	4	12
		Branding	4	10
		Neuroeconomics	4	8
		Prefrontal cortex	4	5
2	**Methods**	Functional magnetic resonance imaging/ fMRI	33	44
		fNIRS	9	13

3.1.5 Citation analysis

Analyzing citations is crucial for gaining insights into global trends in a specific research field, such as neuromarketing, as it provides valuable information about the most frequently cited papers. Future researchers or practitioners can use this information to identify impactful articles. In this study, we analyzed a total of 86 papers that used fNIRS and fMRI tools in neuromarketing research, and identified the most frequently cited articles in Table no. 5, with over 65 total citations (TCs), which investigated consumer behavior in response to marketing stimuli such as branding. Table no. 5 shows that one paper had over 200 TCs, and the article titled "Aesthetic package design: A behavioral, neural, and psychological investigation," which used fMRI tools and was published by the Journal of Consumer Psychology, was the most cited article with 281 TCs. The second most cited article was "A functional magnetic resonance imaging study of neural dissociations between brand and person judgments," published by the Journal of Consumer Research, with 193 TCs, which also used fMRI tools. Furthermore, four papers had between 150 and 100 TCs, while three articles had less than 100 TCs, with the least cited article being "Near-infrared spectroscopy (NIRS) as a new tool for neuroeconomic research," with 66 TCs.

Table no. 5 – The top cited document (minimum 65 citations)

Paper	Year	Journal	Tool	Type	TCs by the end of 2022
"Aesthetic package design: A behavioral, neural, and psychological investigation"	2010	Journal of Consumer Psychology	fMRI	A	281
"A functional magnetic resonance imaging study of neural dissociations between brand and person judgments"	2006	Journal of consumer research	fMRI	A	193
"How we relate to brands: Psychological and neurophysiological insights into consumer–brand relationships"	2012	Journal of Consumer Psychology	fMRI	A	147
"The neural mechanisms underlying the influence of pavlovian cues on human decision making"	2008	Journal of Neuroscience	fMRI	A	134
"Defining neuromarketing: Practices and professional challenges	2010	Harvard review of psychiatry	-	R	119

Paper	Year	Journal	Tool	Type	TCs by the end of 2022
Hypothetical and real choice differentially activate common valuation areas”		Journal of neuroscience	fMRI	A	106
“Applications of functional magnetic resonance imaging for market research”	2007	Qualitative Market Research: An International Journal	fMRI	A	88
“Consumer neuroscience for marketing researchers”	2018	Journal of Consumer Behaviour	-	R	74
“Near-infrared spectroscopy (NIRS) as a new tool for neuroeconomic research”	2014	Frontiers in human neuroscience	NIRS	A	66

4. DISCUSSION

Over time, there has been an increasing interest in utilizing neuroscience tools, such as fMRI and fNIRS, in marketing research to better understand consumer behavior toward advertising stimuli (Alsharif *et al.*, 2021d). In line with this, the current study employed the PRISMA framework to identify pertinent articles that utilized fMRI and fNIRS tools to study consumer behavior in neuromarketing. Ultimately, eighty-six articles and reviews were extracted from the Scopus database using the established procedures. Additionally, bibliometric analysis was employed to reveal global academic research trends in neuromarketing activities, which facilitated the identification of the most productive countries, academic institutions, authors, journals/sources, and trend citations for future studies, ultimately saving researchers' time. Specifically, the analysis revealed the United States as the most productive country, with twenty-five papers utilizing fNIRS and fMRI tools in marketing studies, followed by Germany, Spain, and Australia.

Despite being ranked ninth on the list, the Copenhagen Business School, a Danish institute, published the paper with the second-highest number of citations. Furthermore, Reimann, M. and Kenning, P. were found to be the most productive authors, having published six papers with 468 and 266 TCS, respectively, followed by Krampe, C. and Casado-Aranda, L.A., who published four papers with 65 and 5 TCs, respectively. Analysis of the most prolific journals in neuromarketing revealed that while Frontiers in Human Neuroscience was the most productive journal, publishing five papers with 116 TCs, the European Journal of Marketing had the second-highest citations count with four papers and 101 total citations. This suggests that the number of publications does not necessarily reflect the number of citations. The study titled "Aesthetic package design: A behavioral, neural, and psychological investigation" by Reimann *et al.* (2010), which utilized the fMRI tool, was identified as the most cited article, with 281 total citations, published in the Journal of Consumer Psychology. The second most cited article was "A functional magnetic resonance imaging study of neural dissociations between brand and person judgments," published in the Journal of Consumer Research and also utilizing fMRI, with 193 total citations, written by Yoon *et al.* (2006).

In summary, it has been observed that emerging countries have not made significant contributions to neuromarketing research papers. Consequently, this paper calls upon scholars and researchers from these countries to investigate global academic trends in neuromarketing studies, as this can offer a comprehensive understanding of studies that can be explored in future research.

5. CONCLUSION

In marketing research, traditional self-report methods such as interviews, surveys, and focus groups have been used to better understand consumers' reactions toward marketing activities. However, these methods cannot accurately explain subconscious and unconscious behaviors. Therefore, researchers and marketers have turned to neuroscience tools such as fNIRS and fMRI to measure these concealed responses of consumers. The growing interest in using these tools in marketing research has led to increased academic publications, from one paper in 2002 to 17 papers in 2020, with a slight decline to eight papers in 2022. This study aims to present a comprehensive overview of the global academic trends in neuromarketing, including the leading country, top academic institutions, most prolific authors, most-cited paper, top journals, and a number of citations, with a focus on studies that have utilized fNIRS and fMRI in marketing research.

The study analyzed 86 papers that employed fNIRS and fMRI techniques in marketing research. The results showed that developed countries had the highest number of published papers, with the United States leading at 24 papers, followed by Germany (15 papers), Spain (7 papers), and Australia (6 papers). Most authors produced fewer than five papers, but Reimann, M. and Kenning, P. are the most prolific authors, each with six papers and 468 and 266 citations, respectively. The Frontiers in Human Neuroscience journal had the most publications, with five papers and 79 TCs, while the European Journal of Marketing had four papers and 96 TCs. The study found that the number of publications did not always reflect the number of citations. The paper with the highest number of citations was "Aesthetic package design: A behavioral, neural, and psychological investigation," with 285 citations, followed by "A functional magnetic resonance imaging study of neural dissociations between brand and person judgments" with 195 TCs.

6. LIMITATIONS AND FUTURE DIRECTIONS

The aim of the paper was to minimize methodological restrictions in the study, but some restrictions were still encountered, and suggestions were made for future research. The study focused solely on articles and reviews published in English language journals between 2002 and 2022, which were indexed in the Scopus database. This approach, however, ignored other documents such as conference papers, book chapters, short surveys, editorials, books, and notes, which could lead to bias in the study. To address this limitation, the authors recommend that researchers and marketers from emerging countries should publish their works in this field for future studies. The paper provides a comprehensive overview of the global academic trends of using fNIRS and fMRI tools in neuromarketing activities between 2002 and 2022, based on the analyzed publications.

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