REVIEW ARTICLE

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Electroencephalography in consumer behaviour and marketing: a science mapping approach

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Since its inception, the field of consumer neuroscience and neuromarketing has undergone significant development. The principal objective of this work is to identify current research and to define emerging topics in both consumer neuroscience and neuromarketing using electroencephalography (EEG) since no studies have thus far examined this issue. To this end, a bibliometric analysis was conducted with the Science Mapping Software tool SciMAT. In total, 497 articles published between 2002 and 2022 were examined. The analysis encompassed all research from brain regions, technologies, and marketing which can be applied for a better understanding of consumer behaviour. The main contribution of this work is the comprehensive and objective review of the topic, which highlights the potential interest in applying EEG to emerging technologies (e.g., augmented reality, mixed reality, or virtual reality), tourism marketing communications, healthy food products, consumer willingness-to-pay, service marketing, dynamic stimuli, and consumers' emotions.

Introduction

During the last 20 years, marketing researchers and professionals have witnessed the emergence of a new discipline, namely consumer neuroscience (CNS) and neuro-marketing. This field has an increasing impact on our understanding of how individuals process marketing stimuli using techniques derived from neuroscience (Oliveira et al., 2022). Hubert and Kenning (2008) were among the first researchers to differentiate both terms from an academic perspective, explaining that CNS encompasses the study of cognitive and affective processes that concern consumption, their psychological interpretation, and the behaviours triggered by them. Neuromarketing then applies the findings from CNS in the scope of managerial practice.

The increasing relevance of these research areas is indicated by the growing interest in science and practice, as evidenced by the works of Harris et al. (2018), Cherubino et al. (2019), and Karmarkar and Plassmann (2019) who provide an overview of consumer neuroscience and discuss when and how it is useful to integrate neurophysiological data into research conducted in business fields. Furthermore, Zoëga Ramsøy (2019) suggests a basic foundation for the use of neuroscience and related methods in studying advertising effects. Other authors have used neuroscientific and physiological methods to analyse pricing (Boz et al., 2017; Kong et al., 2019), text (Kong et al., 2019), logos (Lourenção et al., 2020), and images for advertising purposes (Muñoz-Leiva et al., 2018; Kong et al., 2019; Espigares-Jurado et al., 2020; Lourenção et al., 2020;

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Zhao et al., 2021). In addition, numerous conferences, calls for papers from prominent scientific journals, and calls for research by institutes such as the Marketing Science Institute focus on this subject. CNS and neuromarketing have also been included in the Marketing Science Institute's bi-annual Research Priorities since 2016. This demonstrates the need to understand consumer behaviour through neuroscientific and psychological techniques and to identify the advances in the field (Marketing Science Institute, 2016, 2018, 2020, 2022).

These methods have been used in academic research for more than two decades and have been applied in a diverse range of scientific areas ranging from psychological and medical diagnoses to studies on tourism or sports sciences. Studies concerning marketing involving these methods began to emerge in the 2000s. Among other aspects, these focused on the fact that advances in scholarly understanding of consumer behaviour are closely related to knowledge of consumer psychology and of the technologies that can be implemented as methodological research tools (Smidts, 2002).

From its inception to the present day, CNS and neuromarketing have continued to thematically evolve in accordance with the particular interests of numerous researchers. For instance, the last two decades have witnessed several hundred studies in the realm of commercial communication, such as advertising effectiveness with banner type and engagement as moderators (Muñoz-Leiva et al., 2018) and the effectiveness of web advertising through attention and memory (Kong et al., 2019). Both these studies used eye-tracking technology. Other studies identified how visual attention to social media impacts the intention to visit restaurants using electroencephalography (EEG) (Simonetti and Bigne, 2022), and analysed consumers' conscious and unconscious reactions to food packaging using both EEG and skin conductance techniques (García-Madariaga et al., 2019). Research has also analysed users' responses to influencer advertising through EEG and eye-tracking technology (Pozharliev et al., 2022), and discussed the potential of neuroscientific methods in the service field (Verhulst et al., 2020).

It is important to address that not all neuroscience and physiological techniques are suitable for measuring all types of marketing stimuli (Murray and Antonakis, 2019). Of all the physiological and neuroscientific methods used in CNS, an EEG seems to be one of the most powerful technologies, particularly in the analysis of perceptual constructs (Hubert and Kenning, 2008; Harris et al., 2018, Tivadar and Murray 2019; Aldayel et al., 2020). This methodology improves the internal validity of studies on consumer psychology, enables real-time analysis, and incurs lower up-front investment than other technologies used in the field (see Lin et al., 2018). Despite its huge relevance and the wealth of EEG literature related to consumer behaviour, no studies examine the range of topics in which EEG was used over the last decades. Therefore, there is a need to organise all existing information on this field of research. For this purpose, bibliometrics is a highly appropriate technique, as it uses various quantitative measures on a consistent set of bibliographic data.

To date, few investigations have identified what marketing themes and constructs can be analysed with different neuromarketing technologies. Some studies analysed the potential of eye tracking and its suitability in examining marketing topics (Zuschke, 2020; Muñoz-Leiva et al., 2022). Similarly, the work by Caruelle et al. (2019) used a skin conductance method to understand consumer emotions. Based on the above, a bibliometric study is required that captures the significant volume of scientific information generated around EEG in marketing and consumer behaviour over the last two decades. This is to address the following objectives:

1. To analyse the evolution of marketing and consumer behaviour research topics over the years using EEG.
2. To identify current research topics addressed through EEG-based methods and emerging topics in the field.

To achieve these objectives, scientific output over the timeframe under study was identified through an analysis of the main themes associated with the application of EEG in marketing and consumer behaviour. This bibliometric approach enables organising existing scientific information, identifying research gaps, and offering recommendations for potential new academic and professional studies based on bibliometric research methodology (Muñoz-Leiva et al., 2022).

This study makes two main contributions: (1) It maps the evolutionary path of the EEG-based CNS and neuromarketing literature by quantifying, aggregating, and ranking key topics, offering broad insight into its intellectual structure. (2) It derives emerging topics that are currently being addressed and could guide future EEG-based CNS and neuromarketing scholars.

The paper is structured thus: Following this introduction, the section "EEG-based in consumer behaviour and marketing" provides a theoretical background of EEG, how it operates, and its functionalities, including the application of this technology in marketing and consumer behaviour research. Section "Methods" presents the stages of the methodology followed in this study, detailing the bibliographic information database selected, periods under study, evolution of the publication of EEG research, and bibliometric analysis procedure performed using SciMAT software. Section "Results" provides the results of the EEG research topics for marketing and consumer behaviour by period, offering a longitudinal perspective. Section "Discussion" discusses the results, and the section "Research agenda" proposes a research agenda based on the emerging topics identified. Finally, the main conclusions are presented in the section "Conclusions". The paper concludes by exploring the theoretical and practical implications of the work presented, the limitations of the study, and issues to be considered in future research. It is expected that this work will serve as a guide for researchers and academics in their future research through the use of EEG in marketing and consumer behaviour. It also extends the work of Lim (2018) by providing a holistic view of the field and identifying emerging research topics that require further investigation.

EEG-based in consumer behaviour and marketing

In recent years, researchers have ventured into the use of neuroscience methods including EEG; fMRI; magnetoencephalography (MEG); positron emission tomography (PET); functional near-infrared spectroscopy (fNIRS); and other biometrics and physiological tools including eye-tracking, facial coding, skin conductance, and heart rate, to better evaluate consumer responses (Lin et al., 2018; Karmarkar and Plassmann, 2019; Bazzani et al., 2020).

The main brain-based methods used in the field of CNS and neuromarketing are EEG and fMRI. fMRI is a neuroimaging technique used to measure the amount of deoxygenated haemoglobin during neuronal activity. However, its temporal resolution is relatively lower than that of EEG (Lin et al., 2018). Furthermore, MEG and PET are not preferred devices in CNS and neuromarketing research because of their higher cost and technical complexities (Karmarkar and Plassmann, 2019; Bazzani et al., 2020).

EEG is a non-invasive electrophysiological technique that measures brainwave activity via sensors (electrodes) and is one of the most commonly used neuroimaging techniques (di Flumeri et al., 2019; Bazzani et al., 2020). When neurons communicate with each other, the electrical activity produced can be measured

on the scalp via electrodes. Electrodes are usually located according to the international 10–20 system, which is based on their scalp-related location, and are directly applied to the scalp or in a head cap (Lin et al., 2018; Bazzani et al., 2020).

The main advantage of EEG over fMRI, MEG, and PET is that it provides real-time data, great temporal, and potentially good spatial resolution (with a high number of electrodes). It is also less invasive and a relatively less expensive method of measuring brain waves. Other advantages include a more natural setting and portability (allowing its use in environments outside the laboratory with the more recent dry cap and wireless EEG), the ability to identify and remove artefacts related to movement with relative ease, and lower per-subject costs (enabling wider research accessibility) (Lin et al., 2018; di Flumeri et al., 2019; Karmarkar and Plassmann, 2019; Tivadar and Murray, 2019). However, what really stands out in EEG is its usefulness in capturing direct and objective data to further assist researchers in (1) understanding the cognitive and emotional processes involved in information processing and decision-making and (2) understanding implicit processes often difficult to measure when using self-report measures such as surveys (Lin et al., 2018). When used appropriately, EEG precision enables researchers to capture responses to common marketing topics including advertising, pricing, and branding. Furthermore, the use of EEG methods can assist in discerning cause-and-effect relationships between marketing stimuli and their associated cognitive responses (Lin et al., 2018).

Regarding EEG types and electrodes, EEG systems improve electrode–skin conductance with gels or solutions. However, with the more recent wearable and dry EEG caps, some advances have been made in the use of dry electrode systems that do not require gels or solutions, which enables bringing research from the laboratory to applicative fields (di Flumeri et al., 2019; Tivadar and Murray, 2019). On the other hand, the number of electrodes used to explore brain activity can vary from 3 to 256 (Tivadar and Murray, 2019; Bazzani et al., 2020; Sanders et al., 2020). In fact, a study conducted by di Flumeri et al. (2019) demonstrated the high quality achieved by dry EEG caps, since all the electrodes used guaranteed the same quality levels as wet electrodes. This reduces the set-up time and increases user comfort.

Using EEG methods, consumer responses are typically revealed in two ways: event-related potential (ERP) components and EEG neural oscillations (also called 'waves' or 'bands'). ERP is an event-related potential used to understand perceptual or cognitive processes in response to sensory stimuli, and can be positive (P) or negative (N), which are reflected in the direction of the deviation from the baseline. Table 1 shows the most popular ERPs (Lin et al., 2018) and why they are of interest in CNS and neuromarketing research.

On the other hand, EEG neural oscillations can be divided into delta band (0.2–4 Hz), theta (5–8 Hz), alpha (8–14 Hz), beta (15–29 Hz), gamma (30–90 Hz), and very high frequencies (>90 Hz), which measure the voltage of electrical potential and frequency of oscillations (Hz) in brain activity (Tivadar and Murray, 2019; Bazzani et al., 2020).

Some researchers (Lin et al., 2018; Gountas et al., 2019; Karmarkar and Plassmann, 2019; Tivadar and Murray, 2019; Bazzani

et al., 2020) highlighted that EEG can be used to measure arousal and engagement responses to information, attention and memory, attitudes and preferences, decision-making, affect and emotions, perception, motivation, and their neural correlates. Other researchers noted that EEG can measure constructs such as trust and risk, reward, or willingness-to-buy in real-life purchasing situations (Harris et al., 2018; Aldayel et al., 2020). This emphasises the importance of EEG in consumer behaviour research.

Finally, a common complaint regarding the use of neuroscience technologies to study consumer behaviour is the use of small sample sizes, which is perceived as resulting in low statistical power. However, the fundamental biological composition of the brain does not vary as widely as other behavioural variables. Actually, the experimental design used for conducting CNS studies is much more controlled than behavioural experiments (Lin et al., 2018), thus being valuable in the consumer behaviour field.

Methods

Bibliometric analyses have gained research relevance in recent years. Their utility in scientifically mapping a given field of study has aroused interest among researchers because it enables the identification of thematic evolution patterns, the principal purpose of which is to allow researchers to gain a more rigorous understanding of large unstructured databases (Kuc-Czarnecka and Olczyk, 2020). Bibliometric analysis summarises the conceptual structure of a particular field, facilitating the identification of relationships between its various sub-disciplines, themes, and articles (Cobo et al., 2011, 2012; Gutiérrez-Salcedo et al., 2018). In this study, SciMAT software was used to complete a bibliometric analysis of the CNS and neuromarketing field.

SciMAT is an open-source science mapping software that helps researchers carry out the different steps of the science mapping workflow into a single software, from data loading and pre-processing of the raw data to the visualisation and interpretation of the results (Cobo et al., 2012).

The relevant data for this study were extracted from the Web of Science (WoS) database. The WoS database is the best source of international multidisciplinary quality scientific output (Montero-Díaz et al., 2018; Muñoz-Leiva et al., 2022). Moreover, WoS includes more than 21,400 journals and its main part is Core Collection, which includes six citation indexes: Science Citation Index Expanded, Social Sciences Citation Index, Arts & Humanities Citation Index, Conference Proceedings Citation Index, Books Citation Index, and, Emerging Sources Citation Index (Pranckutė, 2021). Scopus is a major alternative to WoS (Pranckutė, 2021; Muñoz-Leiva et al., 2022), covering a large number of documents (Visser et al., 2021). However, the extent of content overlap between WoS and Scopus was determined to be varying greatly across disciplines (Pranckutė, 2021). In this regard, following the recommendations of Muñoz-Leiva et al. (2022), and finding that the list of records provided by Scopus has a number of citations per year out of total citations (399) lower than WoS (514), we opted for WoS to carry out our exhaustive search.

Table 1 Most popular ERPs in CNS research.	
P100 (P1)/N100 (N1)	Sensory processing
P200 (P2)	Selective attention, working memory, earliest ERP component to respond to affective valence
N200 (N2)	Cognitive control
P300 (P3)	Decision-making, memory processes, propensity to buy.
N400 (N4)	Language component (brand name product incongruities)
LPP	Affective perception, modulation of emotions.

The WoS database constitutes the quality benchmark of academic databases, and its Journal Citation Reports offer unbiased (publisher-neutral) information together with the most important bibliographic references in the academic literature (Gutiérrez-Salcedo et al., 2018). All of these considerations contribute to WoS being one of the most relied-upon databases for different context studies such as customer relationship management (Liu et al., 2020), customer experience (Sindhu and Bharti, 2020), eye-tracking technology in marketing research (Muñoz-Leiva et al., 2022), advertising (Sánchez-Núñez et al., 2021), industrial marketing (Valenzuela Fernandez et al., 2019), sustainability, and tourism marketing (Cavalcante et al., 2021; Pahrudin et al., 2022).

Sample and research design. To understand the current state of the art and establish potential future trends in our field of interest, we conducted an advanced search of the WoS Core Collection. The keywords used were selected based on those found to be most frequently used by authors in the field. First, we used a basic search string using ('Consumer neuroscience' or 'Neuromarket-ing') and ('EEG' or 'electroencephalography'). This search string yielded a set of documents. After reviewing the keywords used in those papers, we built a definitive search string by adding new keywords that did not appear in the previous search string. Specifically, the keywords used had to be included in the Title, Abstract, Author given Keywords, or Source. The types of documents searched, the language selected, the time period, and the categories taken into account can be consulted in Table 2.

This left us with 497 articles with which to conduct the bibliometric analysis. All information relevant to this work can be found at the end of the paper, in the data availability statement, and be downloaded from an Open Access repository.

The bibliometric analysis encompassed all research from the last 20 years on brain regions, EEG, and marketing, which relates to consumer behaviour themes investigated over the last two decades. Three periods of study were established according to the number of publications per year (Fig. 1), showing the frequency of EEG use in CNS. The first period, 2002–2010, roughly corresponds to the first decade in which the initial acceptance of

Table 2 Advanced search.	
Search string	(TS = ("consumer" OR "customer" OR "buyer" OR "consumer neuroscience" OR "consumer-neuroscience" OR "neuromarketing" OR "neuro-marketing" OR "neuromarketing research" OR "consumer research" OR "customer research" OR "consumer behavior" OR "consumer-behavior" OR "consumer behaviour" OR "consumer-behaviour" OR "customer behavior" OR "customer behaviour" OR "customer-behavior" OR "customer-behaviour" OR "consumer behavior research" OR "consumer behaviour research" OR "customer behavior research" OR "customer behaviour research" OR "consumer habits" OR "customer habits" OR "consumption habits" OR "consumption behaviour" OR "consumption behavior" OR "consumption" OR "marketing") AND TS = ("EEG" OR "Electroencephalography" OR "Electroencephalogram" OR "electroencephalograph" OR "electroencephalographic")
Time period	2002 or 2003 or 2004 or 2005 or 2006 or 2007 or 2008 or 2009 or 2010 or 2011 or 2012 or 2013 or 2014 or 2015 or 2016 or 2017 or 2018 or 2019 or 2020 or 2021 or 2022
Document types	Article or Review Articles
Language	English
WoS categories	Neurosciences or Business or Psychology or Management or Communication or Economics or Psychology Biological or Psychology Experimental or Psychology Multidisciplinary or Multidisciplinary Sciences or Behavioral Sciences or Hospitality Leisure Sport Tourism or Psychology Applied or Ethics or Neuroimaging or Social Issues or Sociology or Psychology Social or Information Science Library Science
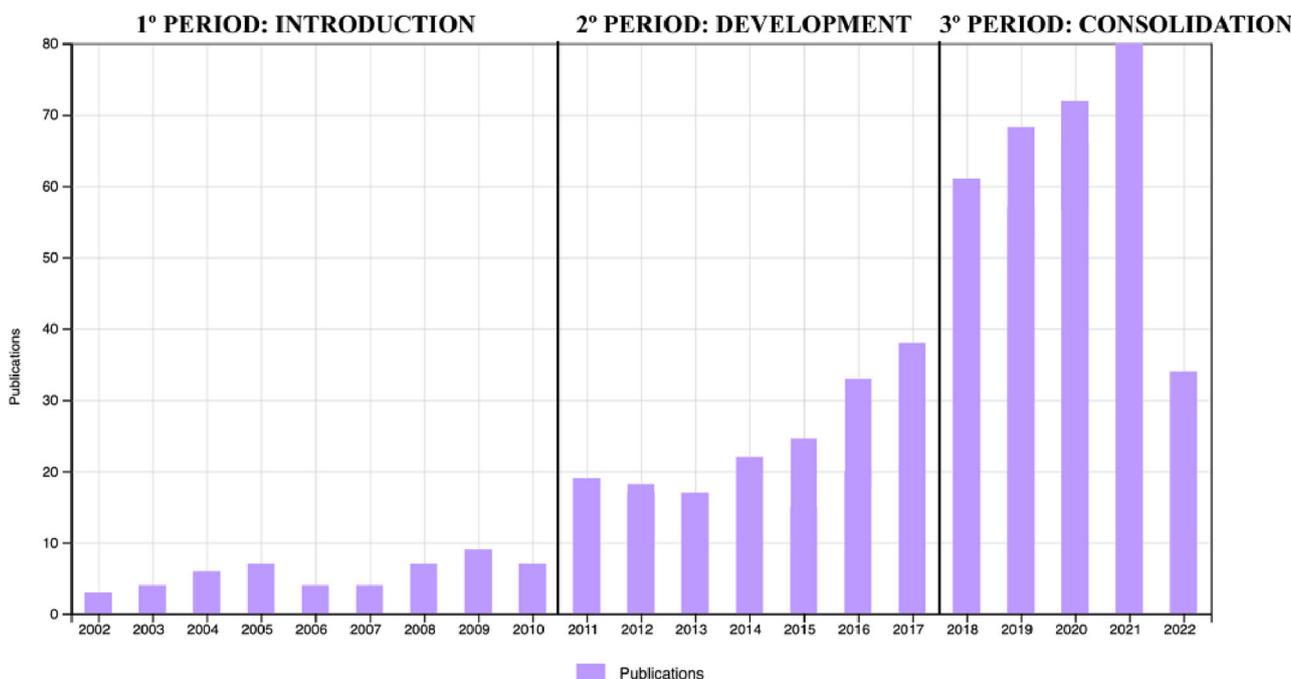
Fig. 1 An overview of EEG-based CNS and neuromarketing studies in Web of Science. Data accessed: July 2022.

EEG technology in the field was demonstrated. In the second period, 2011–2017, the use of EEG experienced a growth phase. During the third period, 2018–2022, extensive use of EEG in CNS studies is evident.

To build the knowledge base with which to work in SciMAT, the raw bibliographic data retrieved from WoS needed to be checked for errors and duplication (Cobo et al., 2012). SciMAT offers several tools to complete this process, including the option to edit individual entities such as the author or journal title, and the facility to merge synonymous and/or misspelled terms. Manual screening to check the retrieved studies was performed before the analysis. The validation criteria were that the article extracted must be related to CNS, neuromarketing, consumer behaviour, and/or EEG technology. After preparing the knowledge base, a network was constructed using the unit of analysis

(in our case, keywords) in order to explore the relationships between keywords through a co-occurrence matrix (Cobo et al., 2012). As a final step, before grouping the data using a clustering algorithm, keyword frequencies were normalised using the equivalence index (Cobo et al., 2012). Figure 2 shows a schematic of the analysis process.

The science map produced by SciMAT can be visualised in various ways, but most commonly using a strategic diagram. To better understand the results, the composition of the diagram is briefly explained in Fig. 3. The strategic diagram comprises two orthogonal axes, where network centrality is represented on the x-axis and density on the y-axis. Centrality is a measure of the degree of interaction between topics. Density, on the other hand, indicates the degree of interaction within a given topic, such that higher-density themes have more in-depth development (Cobo et
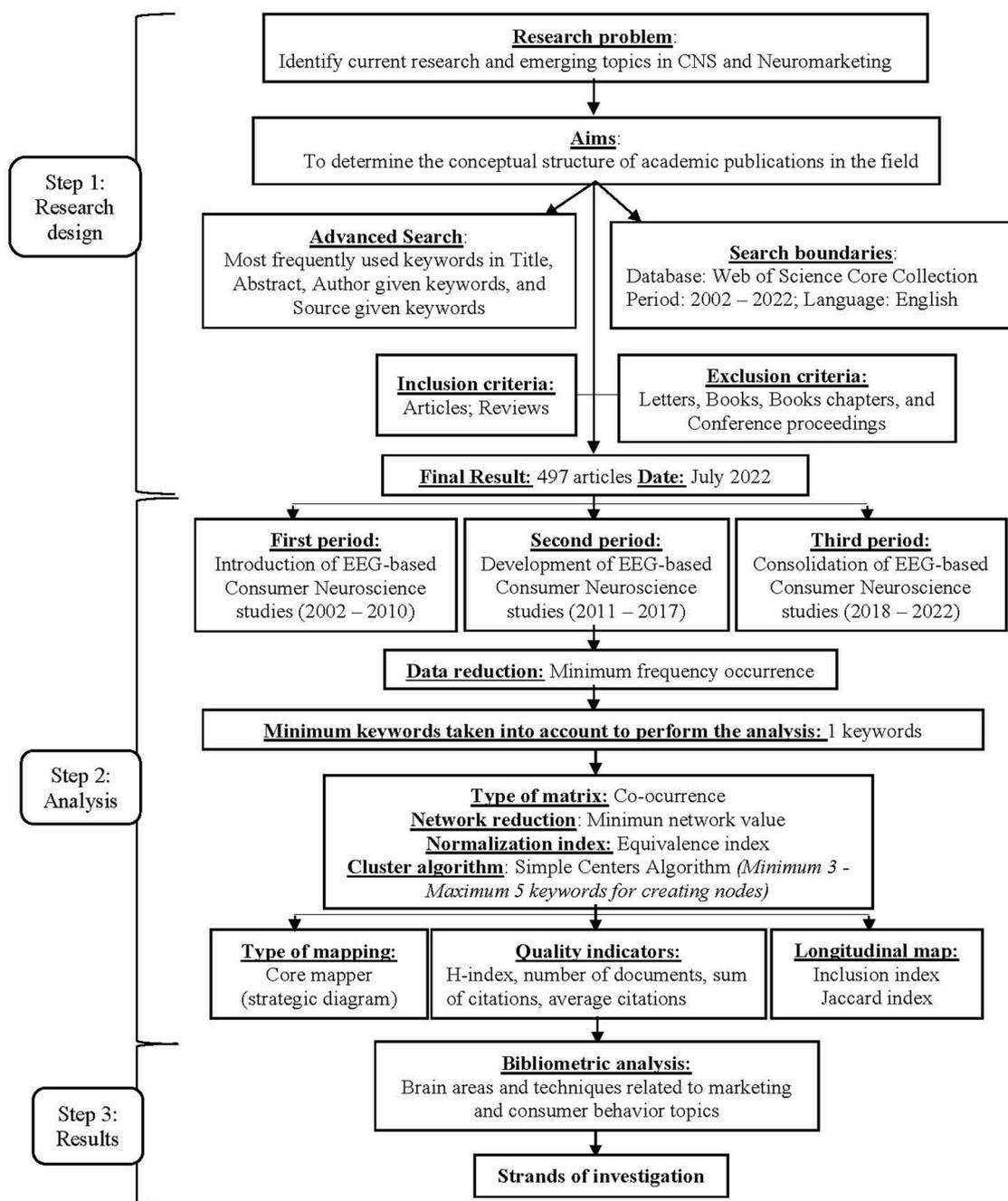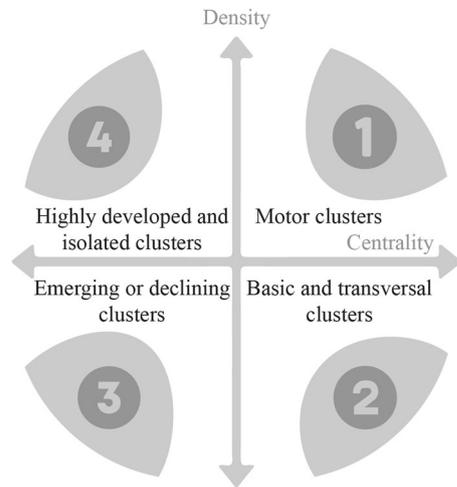

Fig. 2 Analytical process implemented.

Fig. 3 Strategic diagram. Adapted from Cobo et al. (2012).

al., 2011). Thus, the four quadrants of the strategic diagram correspond to four types. Cobo et al. (2012) explained how researchers analyse the results of the strategic diagram, starting with the upper-right quadrant and moving in a clockwise direction around the diagram:

- *First quadrant 'motor clusters'*: Topics are very well developed internally and externally with respect to others in the diagram. These themes are highly relevant and determine the overall shape of the wider discipline.
- *Second quadrant 'basic and transversal clusters'*: Topics are essential to the field of investigation and require further research.
- *Third quadrant 'emergent or declining clusters'*: Topics are underdeveloped and poorly related internally and externally. They might be emergent or declining depending on whether they have been studied in depth in the past.
- *Fourth quadrant 'highly developed and isolated clusters'*: Topics are very specialised or highly developed internally but poorly interrelated with other topics.

Results

The results are presented separately for the three different periods: 2002–2010, 2011–2017, and 2018–2022. Each subsection provides a detailed description of the topics associated with the identified areas, represented by different colours: marketing (purple), neuroscientific techniques (orange), and brain areas studied (blue). Figure 4 provides an overview of these findings, offering a comprehensive visual representation of the research landscape.

Research topics from 2002 to 2010. The first period of study, 2002–2010, reflects a phase where the application of EEG in CNS was in its infancy. There are very few published articles from this period, and the topics researched are very general. Regarding topics corresponding to marketing (purple nodes), prior literature states that in the first decade of CNS, the focus was on the four P's: product, price, promotion, and place (Smidts et al., 2014). Specifically, EEG was used to evaluate the cognitive process triggered by different food products and advertisements. Entering the period 2011–2017, the food products theme evolved, demonstrating a thematic evolution from an emerging theme in 2002–2010 to a highly developed one in 2011–2017. While in this first period (2002–2010), advertising is considered a basic and transversal theme, indicating an interest in studying brands' communication using

EEG. Two articles associated with this period must be taken into consideration. One studying advertisements' effectiveness through brain asymmetries (Ohme et al., 2010), and another exploring the potential of EEG in analysing advertisements (Astolfi et al., 2008).

Regarding physiological and neuroscientific techniques (orange nodes), the tool *heart rate* is highlighted in the first time period because of its combination with EEG in CNS studies. Aligned with the extant literature, this first period was characterised by physiological techniques (Hubert and Kenning, 2008). However, *heart rate* appears in the third quadrant, which indicates that it should be considered a declining theme because it does not appear in later periods. The results indicate *oscillations* as a highly developed topic thanks to advances in medicine (Hallschmid et al., 2002; Masaoka et al., 2005; Herrmann and Debener, 2008). Furthermore, this theme evolves during the second period diverging to form: Theta waves (Vecchiato et al., 2014) and ERP (Telpaz et al., 2015).

Finally, considering areas related to brain areas (blue nodes), two topics stand out: *frontal EEG asymmetry* and the *brain*. These key terms refer to studies on the brain's frontal cortex, specifically asymmetries in activity between the two hemispheres. Brain activity *asymmetry* is a driving theme that has captured the attention of numerous researchers (Ariely and Berns, 2010; Ohme et al., 2010). Thus, in this early phase, it is emphasised how the positive and negative effects of stimuli could be assessed by observing such phenomena. Indeed, it has been shown that activity in the left frontal region of the brain is associated with positive responses to a given stimulus (liking), whereas activity in the right region indicates negativity (dislike) (Aldayel et al., 2020).

Research topics from 2011 to 2017. The second period 2011–2017, is the most significant one in terms of scientific productivity. Regarding marketing, the topic of *neuroeconomics* stands out, especially as applied to *neuroscience* and the study of *consumer responses* to marketed *products*. Although *neuroeconomics* is classified as a precursor discipline in *consumer neuroscience* (Kenning and Plassmann, 2005; Smidts et al., 2014), it remained of research interest throughout this period.

Consumer response appears as a basic and transversal theme in marketing. This is linked to research on online advertising and product placement recall (Barnett and Cerf, 2017; Guixeres et al., 2017). Furthermore, this topic is related to the analysis of implicit and explicit emotions aroused by food products (Walsh et al., 2017b, 2017a). This keyword maintains its position as a fundamental and transversal theme moving into the following period, 2018–2021.

The term *product* can be distinguished as a highly developed theme, appearing in the fourth quadrant, and is seen in association with studies using EEG to examine product selection and preference (Apriliantya et al., 2016; Guo et al., 2016). Considering neuroscientific techniques, in this period, studies involving *oscillations*, a theme already identified in the previous period, can be delineated into studies using one of two methods to analyse brain activity: those using frequency bands, particularly *Theta*, or those using *ERP* (Lin et al., 2018). Studies involving *Theta* waves are an emerging phenomenon and used to link patterns of brain activity to particular stimuli such as advertising spots, tourism images, and product perception (Aldayel et al., 2020). Interest in ERP increases during this period given its ability to predict consumer preferences (Telpaz et al., 2015).

Concerning the research on brain areas, the interest in studying the prefrontal cortex increased due to the greater spatiotemporal resolution of EEG. In particular, EEG was used here to measure the effects of stimuli processed in the prefrontal cortex, such as
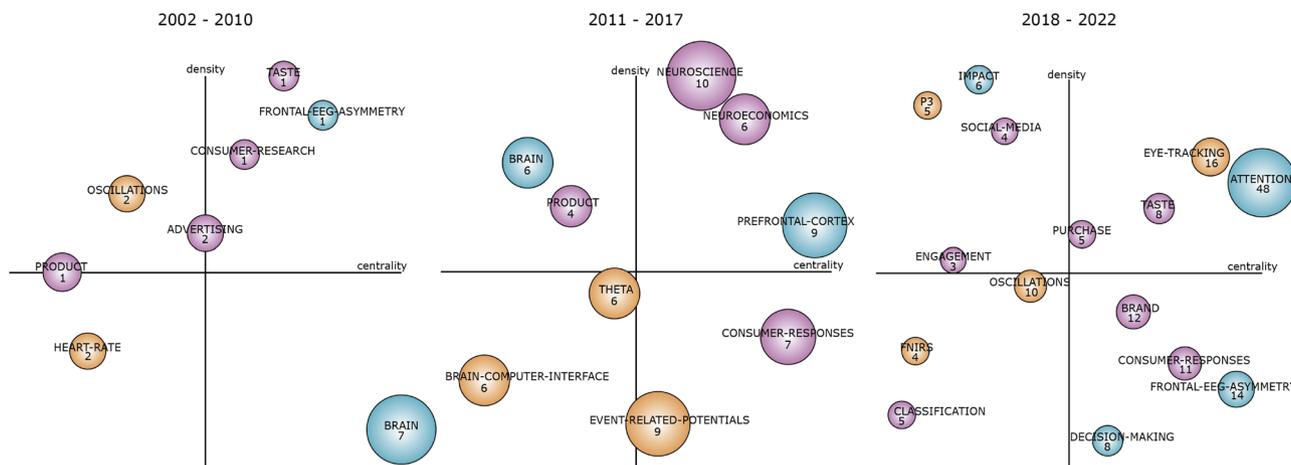
Fig. 4 Conceptual structure in EEG-based CNS and neuromarketing studies. Purple nodes are referred to themes that correspond to marketing topics. Orange nodes are related to physiological and neuroscientific techniques. Blue nodes are associated with brain areas.

attention, decision-making, motivation, and emotional expression (Aldayel et al., 2020).

Research topics from 2018 to 2022. The final period, 2018–2022, represents a significant development in the conceptual structure of the discipline. Driving themes in the area of marketing include *taste* and *purchase*, with the aim of understanding how consumers respond to food products as well as to healthy and unhealthy snacks. Brand and consumer responses turn out to be basic and transversal themes, in the analyses of consumer preferences and perceptions of food and beverages, and electronic devices. In addition, a new term, *classification*, emerges to capture researchers' attention during this period. Here, the focus is on categorising consumer responses to products that are either branded or not.

Regarding neuroscientific techniques, *oscillations*, started to experience a decline from its position as a highly developed topic between 2002 and 2011. Generally, the specialist literature no longer refers to oscillations or waves, but rather to frequency bands or ERP. In fact, the measurement of *P3*, a type of ERP, emerges and soon comes to dominate this area of work. Its potential is linked to the processing of attention, recall, and decision-making. The applicability in the area of marketing is very high (Lin et al., 2018), given its connection with social media and consumer engagement analysis.

Another technique known as *eye tracking* also emerges as a technology used in combination with EEG in CNS. The current high level of interest in this technique highlights it as a driving theme during this period of study. Indeed, only eye tracking and EEG demonstrate research trends in CNS during this time.

Finally, for the study of brain processes and brain areas, a stand-out theme is consumer *attention*. This theme is highly relevant and strongly linked to the study of recall and emotional response using ERP. The analysis of the *impact* on consumers by different marketing variables is also a highly developed theme in this period. Furthermore, the topic of *frontal EEG asymmetry* is now a fundamental and transversal brain area topic, despite that it was a driving theme in the period 2002–2011. This finding suggests the need to continue using brain asymmetry measurements to investigate the positive and negative valences of marketing stimuli, complementing it with other techniques such as facial coding or electromyography (EMG). Another brain process that constitutes a fundamental and transversal theme is *decision-making*, particularly in relation to the use of EEG to enable the

interpretation of consumer decisions, analysis of consumers' willingness to buy certain products, and heuristics.

Discussion

The scientific output of the last 20 years has driven significant development in the field of CNS and neuromarketing. The current findings shown in this work contain the main topics, the relationships between them, and the evolution of the entire conceptual structure.

In this section, we use a longitudinal evolution map offered by SciMAT (Fig. 5), which provides the temporal progression of topics (Cobo et al., 2012) to obtain a dynamic perspective of the conceptual structure of published research. The column represents a period, and the lines establish the relationships between different topics over time. A thematic nexus is represented by solid lines displaying when topics share a matching focal item, whereas the dotted lines indicate those topics are related because they share specific keywords in common. In addition, the thickness of the lines indicates the inclusion index and the volume of the spheres is proportional to the number of published documents associated with each theme (Cobo et al., 2011, Murgado-Armenteros et al., 2015). A summary of the thematic areas is as follows:

- Food research
- Analysis of product attributes
- Consumer willingness to pay
- Research on TV commercials
- Consumer decision-making
- Research on consumer emotions
- Healthy products
- Advertising
- Consumer preferences
- Consumer lifestyle

First, the *food research* area was studied in the two first periods using the concept of consumer research, and it emerged fully as a topic in the last period. Relating this issue to the results above, the topic has been studied by analysing the attention processes related to food products (García-Madariaga et al., 2019; Moya et al., 2020), store illumination as a heuristic for food shopper response (Berčík et al., 2016), decision-making processes (Zhang, 2018), choice processes associated with the acquisition of food products (Stasi et al., 2018), and recall (Park et al. 2011). There is much scientific production related to food research in the current period, determining one important area addressed by EEG in the
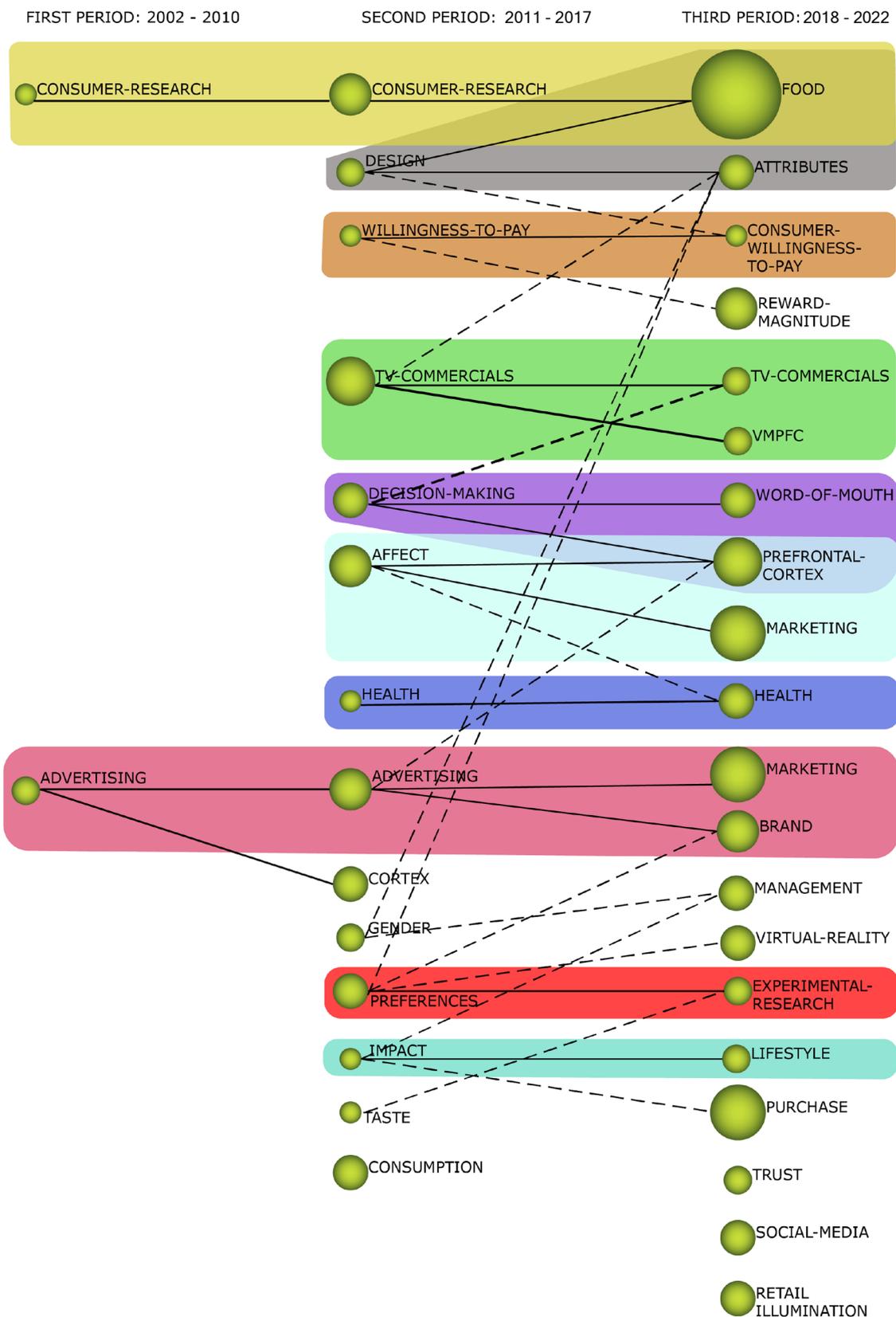
Fig. 5 Longitudinal evolution map in EEG-based consumer neuroscience.

CNS and neuromarketing field. Some advances have already been made in this domain, such as the work of Costa-Feito and Blanco-Moreno (2023), where they investigate the conscious and unconscious perceptions of healthy food, through CNS and Artificial Intelligence techniques. However, as demonstrated in this study, the implementation of EEG in food research allows not only the understanding of perception but also decision-making, recall, and willingness-to-buy.

Second, the *analysis of product attributes* is traditionally studied using Fishbein's theory, asking consumers to consciously identify particular attributes and assign them a score based on their importance. As observed in the "Results" section, EEG technology has advanced the understanding of this area (Guo et al., 2016; Schoen et al., 2018) by identifying important features in consumer decision-making processes they are not consciously aware of. For instance, colours, sizes, shapes, sounds, flavours, prices, as well as other characteristics of the products.

Although research on *willingness to pay* has been effectively explored using traditional techniques, some advances have been made through the application of EEG. In the last two periods, some researchers (Barnett and Cerf, 2017; Zhang, 2018, Zoëga Ramsøy et al., 2019) used EEG to determine the neural mechanisms underlying consumers' willingness to pay processes. However, no studies focused on market segmentation and the drivers of perceived value (Bazzani et al., 2020), clarifying this topic as a research priority.

The relevance of *TV commercials* has been deeply investigated in the past using EEG. Some researchers focused on analysing frontal asymmetries (Vecchiato et al., 2011), while others examined affective and cognitive indices such as happiness, surprise, and attention (Yang et al., 2015). New formats of television advertisements (with QR codes or smartphone ad extensions) have opened new research directions where consumers' multi-device interaction can be analysed using EEG techniques. Moreover, commercials are becoming increasingly common on social media platforms, where the different cognitive and affective processes resulting from the use of various platforms can be studied using EEG.

On the other hand, research on *decision-making processes* has evolved towards word-of-mouth. Traditionally, research focus has been on how consumers shape their preferences and make their decisions (Guo et al., 2016), but now, studies tend to examine how perceived source credibility and electronic word-of-mouth influence consumers' decision-making processes (Pozharliev et al., 2022). This issue is part of a new research strand by using EEG.

In addition, the use of EEG to study *consumers' emotions* has been of interest in the last two periods with a focus on identifying the positive and negative valence of emotions (Vecchiato et al., 2014; Bozhkov et al., 2017). A trend of analysing prefrontal cortex signals is observed among consumer emotion recognition-based experiments in the current period (Harris et al., 2019; Rawnaque et al., 2020). This issue is frequently connected to advertising, opening new research lines in real shopping environments where the data collection is more complex due to the difficulty of isolating biases and noises that occur outside the laboratory. Regardless of its application inside or outside the laboratory, it is recommended to combine EEG with facial coding or electromyography (EMG) to identify the specific emotion evoked by the stimulus, rather than just its positive or negative valence.

Health has emerged as a novel research trend, especially in relation to sustainable consumerism and the consumption of healthy products (Stasi et al., 2018; Russo et al., 2020). As an emerging issue, the number of academic publications in this regard is steadily increasing, such as the work conducted by Costa-Feito and Blanco-Moreno (2023). However, more research is needed on how persuasive statements such as 'low in fat,' 'high in protein,' or 'zero sugars' influence consumer decision-making, being the EEG a potential technique to understand consumer perceptions.

In addition, the increasing importance of studies on *advertising* is evident over time. Although these studies did not constitute a motor theme in the early periods, their importance later emerged as a crucial part of other motor themes (consumers' emotions and TV commercials). This trend suggests that advertising will continue to play a key role in the coming years.

Considering *consumer preferences*, EEG-based research is gaining momentum. This issue has also been investigated in relation to virtual reality (Gao et al., 2019), product attributes (Guo et al., 2016; García-Madariaga et al., 2019), and brand preferences (Horska et al., 2016; Schoen et al., 2018). However, little research has been conducted on consumer preferences regarding services. For instance, the differences in cognitive and affective processes involved in enjoying a live show or experiencing it through platforms such as metaverse. Other potential developments in the field can be extended to tourism or aesthetics, where EEG has room for implementation (Aldayel et al., 2020).

Finally, research on *lifestyle* is beginning to obtain scientific results. Although a few studies have analysed consumer responses to retail greenery through a lifestyle centre (Rosenbaum et al., 2019), there is still much to be done on how consumers with different lifestyles process marketing stimuli. This can be accomplished by applying EEG in conjunction with lifestyle questionnaires, which allows to profile the sample and identify the different cognitive and affective responses to products and services in relation to their lifestyle.

Finally, general research interest has focused principally on products during the three periods of study. This opens the possibility of a new research line in the analysis of services. Only three studies appeared during the periods of bibliometric analysis in the tourism research field (Bastiaansen et al., 2018, 2022; Zoëga Ramsøy et al., 2019).

Research agenda

The bibliometric and science mapping analysis provides a foundation for identifying emerging research gaps (Cobo et al., 2011, 2012). Actually, authors such as Sánchez-Camacho et al. (2020), Vila-Lopez and Küster-Boluda (2021), Molina-Collado et al. (2022), Muñoz-Leiva et al. (2022) and Salgado Sequeiros et al. (2022) have used the science mapping approach to identify emerging avenues. Thus, the ten broader areas previously identified can also be used to develop and discuss a research agenda.

A large amount of information collected and analysed has enabled identifying research avenues, which we hope enhance both research and the field.

(1) Issues related to tourism marketing communications and destination marketing in tourists' purchase behaviour require further research. In recent years, a few studies have used neuroscientific and physiological methodologies to investigate tourists' attention to destination images (Zhao et al., 2021), advertising effectiveness on travel websites (Muñoz-Leiva et al., 2018; Kong et al., 2019; Espigares-Jurado et al., 2020), and tourism pricing (Boz et al., 2017). However, much remains to be done in tourism research. For instance, EEG methodology has been applied to measure emotions in tourism destination marketing (Bastiaansen et al., 2018, 2022; Zoëga Ramsøy et al., 2019), but this issue is in its infancy. Despite that, it provides many advantages because EEG is capable of capturing more objective tourists' responses including those that are unconscious (Telpaz et al., 2015) to enhance tourism marketing strategies.

(2) From the perspective of new technological development, more attention must be paid to emerging technologies. Virtual reality, augmented reality, and mixed reality are interesting areas of research. In this regard, recent studies have compared the visit intentions evoked and the process of booking holiday travel in an immersive virtual reality environment (Bigne and Maturana, 2022), and explored the factors that influence consumers' acceptance of augmented reality in the retail sector (Castillo and

Bigne, 2021). These emerging technologies combined with EEG show new trends that can be targeted by CNS and neuro-marketing researchers.

(3) Issues related to healthy food products require further investigation. Previous research focused on how consumers perceive different food packaging (García-Madariaga et al., 2019; Moya et al., 2020), predict food purchases (Kytö et al., 2019), and food product communication (Russo et al., 2020). However, more research is needed on how healthy habits and lifestyles influence consumers' perception of food products and their decision-making process.

(4) Previous research on willingness to pay focused on how consumers perceive different payment platforms such as credit cards or PayPal (Casado-Aranda et al., 2018). Hence, future studies should explore how consumers perceive new virtual products (e.g., NFTs) or their experience on new virtual platforms (e.g., the Metaverse) and their willingness to pay for them. This new research gap can be addressed using EEG methodology, which will enable researchers to develop strategies for marketing directors.

(5) Domain service marketing has received little attention in terms of EEG methodology. As shown in the discussion section, no practical studies investigate this issue. Thus, doing so would open a future research avenue. Because service marketing has the inherent characteristic of intangibility, images and videos have been used to combat this challenge (Espigares-Jurado et al., 2020). Here, EEG technology can be used to analyse the effectiveness of these images and videos, and as a tool to explore the cognitive and affective processes derived from them.

(6) More research is needed to analyse dynamic stimuli using the EEG method. The bibliometric analysis conducted highlighted TV commercials as one of the most prominent themes. However, most of the stimuli analysed using neuroscientific and physiological methods are static (Muñoz-Leiva et al., 2018; Kong et al., 2019; Zhao et al., 2021), probably because it is difficult to design this type of experiment for recollecting data. Thus, we encourage researchers to investigate marketing dynamic stimuli given that current marketing strategies are in most cases based on stimuli that are continually in motion (2D videos, 360° videos, films or games, among others).

(7) In the bibliometric analysis, the study of consumer emotions emerged as a prominent theme. Topics such as brain asymmetry and affective stimuli can be addressed using the EEG method. However, recent literature demonstrated that attention and memory play an important role in the consumer decision-making process and influence consumer behaviour (Kong et al., 2019; Moyle et al., 2019; Zhao et al., 2021). Thus, researchers should investigate how attention, memory, and emotion influence the consumer decision-making process. It could also be beneficial to implement the Stimulus-Organism-Response model (Mehrabian and Russell, 1974) widely used in CNS and neuromarketing studies.

(8) Finally, numerous researchers emphasised the importance of combining EEG with other physiological techniques such as eye tracking (Cherubino et al., 2019; Karmarkar and Plassmann, 2019; Li et al., 2021). Aligned with this literature, the bibliometric analysis here showed that eye tracking is an important tool to use alongside EEG. Thus, both methodologies should be used in future research (among others) to provide more information on how consumers process marketing stimuli.

Conclusions
The purpose of this research was to synthesise the evolution of EEG as a methodology and research topic in the CNS and neuromarketing field using a bibliometric approach. This study

addresses the research gap in this field, thereby fulfilling the proposed objective.

The sophistication of EEG technology has evolved, giving rise to wearable and dry EEG caps and varying from 3 electrodes to 256. This is also evident in the large volume of studies that use this neuroscientific technique and the multidisciplinary nature of its use, which further enhances its benefits. The need to better understand human decision-making processes and behaviours has been a primary driver for many researchers. As such, more than 1250 scientific articles from more than 100 scientific areas published from 2002 to the present day in the WoS Core Collection have involved EEG. Of the total output, which has witnessed continued growth, neuroscience and business-related studies carry particular weight given the highly transversal nature of this discipline.

Since its origin, the application of EEG has focused on the *product* and *advertising* fields. Subsequently, while this approach has not changed per se, its field of application has broadened to include subject areas such as healthy products, food, retail, TV commercials, social media, tourism destination marketing, and virtual reality. Focusing on this, we observed researchers' interest in identifying the factors that arouse consumers' feelings, decision-making processes, preferences, and willingness to pay by using tools from neuroscience. While significant contributions have been made in the field, there is still room for further development in the analyses of consumers' emotions and perceptions in relation to healthy food, social media platforms, and virtual ones such as Metaverse. EEG could contribute to those analyses, in combination with artificial intelligence and traditional market research techniques.

From the current work, the lines of research that emerged are virtual products and new virtual platforms, service marketing (explicitly, tourism marketing communications), and the analysis of dynamic stimuli. On the other hand, it is important to bear in mind the combination of EEG with other neuropsychological and physiological techniques in practice.

Contributions and limitations
This study directly contributes to the flow of new knowledge in this field and summarises the current findings for both researchers and practitioners, thus having practical and academic implications. Regarding academics, no bibliometric analyses have to date explored the inception and subsequent evolution of EEG in the field of CNS and neuromarketing, despite it being one of the best neuroscientific tools to analyse consumer behaviour (Aldayel et al., 2020). As such, the current work is also expected to serve as a reference point in the academic field. It could also serve as a guide for those interested in starting to work in this discipline.

Regarding practical implications, managers can benefit from this research, as it enhances their understanding of the EEG, CNS and neuromarketing literature and major application themes. This provides opportunities for execution by implementing EEG studies on virtual products or virtual platforms (e.g., NFTs or the Metaverse), applying EEG methods to examine tourism marketing communications or service marketing, and exploring the effectiveness of the dynamic stimuli used to promote products or services (e.g., video advertisements on social networks or 360° videos).

However, this study has limitations that need to be considered. The bibliometric analysis was based on information gathered solely from the WoS Core Collection. While this database brings together the world's most important academic reference material and is considered a benchmark of quality, we recommend that further research be conducted to expand the current study by

including articles from other bibliographic databases, such as Scopus. It could be done in other software such as VoS Viewer, since SciMAT is inconsistent with the structure of Scopus.

In addition, this analysis narrowly focused on EEG-based CNS and neuromarketing studies. It would be interesting to conduct a similar study encompassing other physiological and neuroscientific techniques used in this field, such as eye tracking, skin conductance, or fMRI.

Data availability

The dataset generated during and analysed during the current study are available in the Zenodo repository with the title *EEG-based Consumer Neuroscience and Neuromarketing Dataset* and https://doi.org/10.5281/zenodo.6860680

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