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The application of mobile functional near-infrared spectroscopy for marketing research – a guideline

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Abstract

Purpose – To advance marketing research and practice, this study aims to examine the application of the innovative, mobile-applicable neuroimaging method – mobile functional near-infrared spectroscopy (mfNIRS) – in the field of marketing research, providing comprehensive guidelines and practical recommendations.

Design/methodology/approach – A general review and investigation of when and how to use mfNIRS in business-to-consumer and business-to-business marketing settings is used to illustrate the utility of mfNIRS.

Findings – The research findings help prospective marketing and consumer neuroscience researchers to structure mfNIRS experiments, perform the analysis and interpret the obtained mfNIRS data.

Research implications – The application of mfNIRS offers opportunities for marketing research that allow the exploration of neural processes and associated behaviour of customers in naturalistic settings.

Practical implications – The application of mfNIRS as a neuroimaging method enables the investigation of unconscious neural processes that control customer behaviour and can act as process variables for companies.

Originality/value – This is one of the first studies to provide comprehensive guidelines and applied practical recommendations concerning when and how to apply mfNIRS in marketing research.

Keywords Consumer neuroscience, Neuromarketing, Marketing, mfNIRS, Neuroimaging methods, Guidelines

Paper type General review

1. Introduction

To facilitate progress in the use of neuropsychological methods in marketing research (Kannan, 2017; Shaw and Bagozzi, 2018), this article focusses on the mobile-applicable version of functional near-infrared spectroscopy (mfNIRS) and its use in marketing research. mfNIRS, which uses near-infrared (NIR) light to quantify brain activity, is suggested to be capable of extending knowledge beyond the use of existing marketing methods (Gefen, 2014;

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Krampe *et al.*, 2018a; Krampe *et al.*, 2018b; Gier *et al.*, 2020), whilst providing insights concerning unconscious neural processes.

The method offers advantages over other neuroimaging methods. mfNIRS is, for example, less expensive than the "gold standard" in neuroimaging – functional magnetic resonance imaging (fMRI) – and, most importantly, it is mobile-applicable, which allows the investigation of neural signatures in naturalistic environments. By demonstrating the applicability of mfNIRS, this article highlights new directions for marketing and consumer neuroscience research and demonstrates how marketing researchers from various sub-fields can apply mfNIRS in their work. To this end, the article provides comprehensive guidelines, practical recommendations of *when* and *how* to conduct mfNIRS experiments, in addition to explaining how to collect, analyse and interpret mfNIRS data in marketing and consumer neuroscience research.

The article begins with a brief overview of the fields of consumer neuroscience and neuromarketing and addresses the questions "*Where are we?*" and "*Where are we going?*", looking at both the business-to-consumer (B2C) and business-to-business (B2B) marketing environment. Accordingly, the most common neuroimaging methods applied in marketing research and cognate disciplines are described, followed by an explanation of the basic principles, technical parameters and functionalities of mfNIRS. A particular focus is on the methodological questions of *when* and *how* to conduct mfNIRS experiments as well as how to analyse data, draw possible statistical conclusions and interpret neural results. Lastly, a status-quo analysis of the current integration of the mentioned guidelines is conducted through a systematic literature review of recent fNIRS/mfNIRS studies in the field of marketing research, leading to practical-normative implications and suggestions for future research.

2. Marketing and neuroscience: where we are and where we are going?

Over the past two decades, consumer neuroscience and neuromarketing research has gained credibility and a degree of acceptance in the broader marketing research community (Harris *et al.*, 2018; Lim, 2018; Lee *et al.*, 2018). This development is primarily driven by the belief that the use of neuroimaging methods will help to gain deeper insights into many types of consumer/customer behaviour and processes in a marketing-relevant context, offering the potential to further advance existing theory and practice (Kenning and Plassmann, 2005; Lim, 2018; Plassmann *et al.*, 2015; Zaltman, 2000). Although neuromarketing and consumer neuroscience are predicted to have a bright future (Mansor and Isa, 2020), the fledgling disciplines face several challenges.

The existing concerns that are associated with the usage of neuroscientific methods in marketing research can be seen as a *first challenge* (Plassmann *et al.*, 2015). Consumer neuroscience and neuromarketing are often criticised for "only" measuring brain activity and not actual behaviour *per se* (Plassmann *et al.*, 2015). In response to this concern, it should be evident that the fields of consumer neuroscience and neuromarketing and their associated methods are not intended to replace traditional marketing methods, which measure consumer/customer behaviour. Instead, they should be seen as complementary, with the goal of increasing knowledge about marketing-relevant entities from a neuroscientific perspective. Ideally, consumer neuroscience and neuromarketing research should inspire researchers to use multi-methodological approaches that combine behavioural and neuroscientific methods that capitalise on the strengths of each method (Plassmann *et al.*, 2015).

Another widespread concern associated with the usage of neuroscientific methods relates to the observation that consumer neuroscience and neuromarketing relies primarily on

backward inference to identify psychological mechanisms. Although this is problematic for any research that links neuroscience to behaviour, it is expected to be resolved by using a theory-driven approach to designing studies and/or by applying meta-analytical statistical tools to improve the interpretation of research findings.

The third concern identified by Plassmann *et al.* (2015) refers to the assumption that neuroimaging studies are less reliable and generalisable than traditional marketing studies. This assumption can be refuted based on previous research work demonstrating the possibility of using neuroscientific methods with small sample sizes of 14–29 participants to predict decision-making concerning the choice of products or services with a probability exceeding the level of chance within a population (Berns and Moore, 2012; Boksem and Smidts, 2015; Telpaz *et al.*, 2015). Furthermore, given that the measured neuropsychological processes are based on biological determinants, they can be assumed to occur in similar ways in higher mammals (Seth *et al.*, 2005). There are also statistical and methodological reasons to assume that the relatively small sample size of neuroscientific studies allows the generalisation of findings to the population level (Friston, 1996, 2004, 2012). This is primarily because, according to neuroscientific standards, the stimuli used to gain knowledge are always displayed repeatedly to account for the noise associated with neuroscientific measurements (Plassmann *et al.*, 2015). The actual number of stimuli shown in a neuroscientific study does therefore not differ significantly from that shown in a between-subjects behavioural study, thus providing further confirmation of the statistical power of neuroscientific studies (Plassmann *et al.*, 2015; Hensel *et al.*, 2017).

A *second challenge* is the fact that previous research has focused almost exclusively on entities that can be attributed to B2C marketing, including research questions on how consumers respond to merchandising elements of in-store communication (Krampe *et al.*, 2017; Cakir *et al.*, 2018) or how neuroscience data can be used to predict future consumer behaviour (Knutson *et al.*, 2007; Berns and Moore, 2012; Gier *et al.*, 2020). Although the research findings provided valuable insights that advanced (consumer) theories and provided practical–normative solutions for companies operating in consumer markets, the exclusive focus on consumer neuroscience neglects the fact that neuroscientific approaches can also provide fruitful insights for marketing research in the broader field of B2B marketing (Lim, 2018). Hence, the advantages of neuroscientific methods should not be disregarded in the field of B2B marketing.

Finally, the *third challenge* relates to the limited ecological validity attributed to the mostly stationary neuroimaging methods used in consumer neuroscience and neuromarketing. An aspect that makes it particularly difficult to verify whether research results that have been studied under controlled laboratory conditions or in experiments remain valid in naturalistic contexts or environments.

While the first challenge and related concerns have been –at least partially– resolved in previous research, the second and third challenges remain. There is, consequently, a need for mobile-applicable neuroimaging methods in the field of marketing research that allow to close the ecological validity gap of existing neuroscientific methods and validate data gained from laboratory experiments with data from the real world within the B2C or B2B marketing environment (Boto *et al.*, 2018; Gordon *et al.*, 2018).

3. Neuroscientific methods applied in marketing research

In general, three groups of neuroscientific methods can be identified within the field of consumer neuroscience and neuromarketing (Lim, 2018). The first comprises methods that measure the effects of neural activity patterns (e.g. eye movements, pupil size variation, facial electromyography or skin conductance), and not actual neural activity. A second

group consists of neuroimaging methods, which can be defined as methods that allow the production of *in vivo* images of the human brain (Dimoka *et al.*, 2012). In essence, these methods can be subdivided into two groups: *electromagnetic neuroimaging methods*, which measure immediate neurophysiological responses (e.g. magnetoencephalography/MEG and electroencephalography/EEG), and *metabolic neuroimaging methods*, which are based on human metabolic processes (e.g. fMRI).

Other non-neuroimaging methods are also applied. These methods focus on the physiological effects of neural activity patterns, but do not measure neural activity patterns itself. These neuroscientific methods constitute their own methodological group, which is not further considered in this study (for additional information about these methods, Lim, 2018).

In contrast to electromagnetic neuroimaging methods, metabolic neuroimaging methods measure brain activity based on the premise that active brain regions need more energy and, consequently, more oxygenated blood, which is used as a proxy for quantifying neural activity according to physiological characteristics (Kwong *et al.*, 1992). Indirect neuroimaging methods are thus based on a correlative approach. Another distinguishing feature of neuroimaging methods has to do with the prevalence of its usage, which depends primarily on the research focus, technical capabilities and the functionality of the specific method. The final group of neuroscientific methods is related to those that can be used to manipulate neural activity patterns by interrupting the neural system (e.g. transcranial magnetic stimulation and the direct manipulation of neurotransmitter level within the brain) (Hallett, 2000).

The most common electromagnetic and metabolic neuroimaging methods are summarised in Table 1, along with their advantages and disadvantages in the context of marketing research.

As indicated before, given the limited set of mobile-applicable neuroimaging methods available, previous research indicated that mobile neuroimaging methods, such as mfNIRS, could potentially help to close the mentioned *ecological validity gap* of neuroimaging methods (Boto *et al.*, 2018; Gordon *et al.*, 2018) by answering research questions related to consumer neuroscience and neuromarketing (Kopton and Kenning, 2014; Krampe *et al.*, 2018a, 2018b). mfNIRS might therefore provide a fruitful new avenue for investigating the neural processing and associated behaviour of consumers and customers in real-world B2C or B2B marketing settings.

4. Mobile functional near-infrared spectroscopy

More than 20 years ago, Jobsis (1977) demonstrated the possibility of using NIR light to detect changes in adult cortical oxygenation during hyperventilation (Ferrari and Quaresima, 2012; Kopton and Kenning, 2014). Based on his work and subsequent developments, fNIRS/mfNIRS has recently been applied in several research fields, including neuro-economics (Kopton and Kenning, 2014), shopper neuroscience (Krampe *et al.*, 2018b; Gier *et al.*, 2020), *e*-commerce (Nissen and Krampe, 2021) and neuro-organisational research (Quaresima and Ferrari, 2016), indicating its potential usage in the field of marketing. Although, recent studies suggest that mfNIRS is a suitable method for research in the fields of consumer neuroscience and shopper neuroscience (Krampe *et al.*, 2017; Gier *et al.*, 2020), its application in the field remains limited. Explanations, next to the identified common challenges associated with the use of neuroscientific methods, include the limited or fragmented literature related to mfNIRS in marketing research, the lack of high-quality, user-orientated methodological primers and the lack of clear guidelines concerning how to apply mfNIRS (Lee *et al.*, 2018).

Table 1.
The most common direct and indirect neuroimaging methods applied in consumer neuroscience and cognate research

Neuroimaging method	Advantages	Disadvantages	Related studies	Mobile applicability
Electromagnetic neuroimaging methods				
Magnetencephalography MEG Registration of changes in magnetic streams elicited by the electrophysical signal of neurons	+ Good temporal resolution (neural activity changes can be measured in s) + Non-invasive	– High measurement costs – Relatively complicated data analysis – Poor spatial resolution (limited potential to localise brain activity on the cortex)	Ioannides *et al.* (2000), Zaltman and Kosslyn (2000), Boto *et al.* (2018)	Partial
Electroencephalography EEG Measurement of voltage fluctuations at the surface of the cortex	+ Good temporal resolution (neural-activity changes can be measured in ms) + Moderate equipment costs + Relatively uncomplicated data analysis + Non-invasive	– Poor spatial resolution (limited potential to localise brain activity on the cortex) – Relatively complicated data collection	Boksem and Smidts (2015), Harris *et al.* (2018); Müller-Putz *et al.* (2015)	Partial
Metabolic neuroimaging methods				
Positron-Emission-Tomography PET Nuclear medical technique for analysing indirect, metabolic processes in neurons	+ Good spatial resolution (neural activity of the whole brain can be measured and localised)	– Very poor temporal resolution (compared to EEG) – Invasive	Harris *et al.* (2018)	No
Functional magnetic resonance imaging fMRI Measurement of indirect, metabolic activity using the magnetic properties of blood (the BOLD signal)	+ Very good spatial resolution (neural activity of the whole brain can be measured and localised) + Non-invasive	– High measurement costs – Relatively complicated data analysis – Poor temporal resolution (compared to EEG)	Dimoka and Davies (2008), Dimoka (2010), Falk *et al.* (2016), Hubert *et al.* (2018), Kenning *et al.* (2007), Ogawa *et al.* (1990)	No

By addressing the three obstacles that may prevent marketing researchers from using mfNIRS, the current study aims to increase awareness amongst marketing researchers concerning the possibilities of mfNIRS in marketing research and beyond, to establish the fundamental principles of the neuroimaging method and to evaluate whether their research could benefit from the integration of mfNIRS. It, therefore, addresses (4.1) *the basic operating principle of mfNIRS*, (4.2) *the technical parameters and commercially available mfNIRS systems*, (4.3) *the penetration depth of mfNIRS*, and (4.4) *potential confounding effects that might interfere with the fNIRS signal.*

4.1 Basic operating principle of mobile functional near-infrared spectroscopy

NIR light – or, more precisely, light in a wavelength spectrum of 650–950 nm – has the advantage of being able to pass through biological tissue and non-invasively illuminate cortical tissue in the human brain (Funane *et al.*, 2014; Jobsis, 1977; Kopton and Kenning, 2014; Krampe *et al.*, 2018a, 2018b; McCormick *et al.*, 1992; Scholkmann *et al.*, 2014). The fNIRS method takes advantage of this characteristic, as parts of the emitted and scattered NIR light are absorbed or reflected by oxygenated and de-oxygenated haemoglobin, thereby allowing the indirect quantification of neural activity. More precisely, by using NIR light sources to emit NIR light photons, which always travel through tissue in a "banana shape" (Okada and Delpy, 2003) and by measuring the reflection with NIR-light detectors, this method allows the indirect measurement of brain activity within particular brain regions, defined *ex ante* (Figure 1).

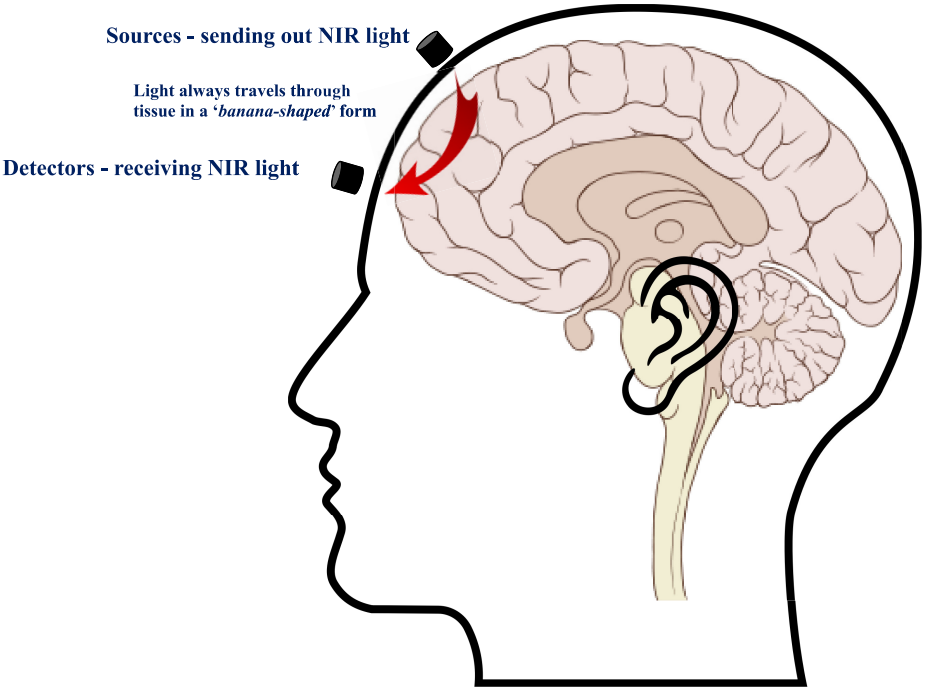

Figure 1.
mfNIRS functionality

4.2 Technical parameters and commercially available functional near-infrared spectroscopy/ mobile functional near-infrared spectroscopy systems

Many fNIRS systems, which are based on specific techniques, are currently available. Some of the underlying techniques have similar characteristics and are associated with possible advantages and disadvantages. Most of the fNIRS/mfNIRS systems that are currently applied are based on the continuous wave (CW) method (Quaresima and Ferrari, 2016; Scholkmann *et al.*, 2014), which is known to be cost-effective, wireless and portable (Kopton and Kenning, 2014). The CW-fNIRS system allows measurement of oxygenated, de-oxygenated and total haemoglobin concentrations, always in relation to a pre-defined reference value of zero (measured initially as a baseline).

A second system applied is the frequency domain (FD) method, which uses intensity-modulated light to illuminate the head, thus measuring attenuation and delay phases of the transmitted light (Quaresima and Ferrari, 2016; Scholkmann *et al.*, 2014). The FD method could hypothetically be seen as a development of the CW-fNIRS method, as it can measure both light-intensity attenuation and phase shift (Fantini *et al.*, 1999). According to the current research, however, there is no advantageous methodological distinction between the FD- and CW-fNIRS techniques (Davies *et al.*, 2017).

A third system is the time domain (TD) technique, which uses short light pulses to illuminate the head and detect the shape of the pulse after propagation through the tissue (Quaresima and Ferrari, 2016). Compared to CW methods, TD techniques tend to have lower temporal resolution and higher costs, and they are unable to represent weak, functional differences in neural activity, due to the lower intensity of the NIR light (Scholkmann *et al.*, 2014).

To decide which system to use, the benefits of the individual mfNIRS system compared to its costs as well as the individual research question need to be considered. More generally, however, relative to FD- and TD-fNIRS systems, CW-fNIRS systems offer the advantages of cost-effectiveness and mobile applicability – two important factors relating to the appropriateness of applying mfNIRS in naturalistic marketing-relevant settings, e.g. during a shopping situation or while exploring interactions processes between value chain actors. In turn, FD- and TD-fNIRS techniques offer the possibility of characterising the optical properties of tissue, thereby enabling the determination of changes in absolute oxygenated and de-oxygenated haemoglobin concentration. Nevertheless, these two techniques require more technical expertise to acquire and analyse data than it is the case for CW-fNIRS systems. Findings that might lead to the conclusion that CW-fNIRS systems are most suitable for marketing research and practice.

In addition to the technical parameters, fNIRS/mfNIRS systems vary in their complexity from smaller two-channel portable fNIRS devices (Adorni *et al.*, 2018; Brugnera *et al.*, 2016; Brugnera *et al.*, 2017) to stationary "whole-head" arrays that integrate several dozen channels and cover the whole human cortex. Whereas these advanced "high-density 3-dimensional whole-head fNIRS system[s] (integrating more than 50 fibre optical bundles)" (Liao and Culver, 2014; Quaresima and Ferrari, 2016; Scholkmann *et al.*, 2014) improve data quality by increasing spatial and temporal resolution, they have the disadvantages of requiring stationary usage, being limited in their flexibility and cable length, in addition to being uncomfortable for participants. As indicated before, to solve the ecological validity gap, this study focusses on battery-operated, multichannel, wireless, mfNIRS systems given that they allow measurements in real-world, naturalistic settings – an advantage that seems particularly important in applied marketing research, considering both B2C and B2B marketing research.

4.3 Penetration depth of near-infrared light

The penetration depth of NIR-light is important for marketing researchers to determine which brain regions and consequently which neuropsychological processes can be measured with mfNIRS. The penetration of NIR light depends, thereby, on the light scattering, absorption rate and separation distance between NIR light sources and detectors. As mentioned before, NIR light photons are known to travel in a "banana shape" through tissue, such that fNIRS/mfNIRS measurements are most sensitive to oxygenated/de-oxygenated haemoglobin molecules 1.5–2.5 cm below the skull. For the actual measurement of neural cortical activity, the penetration depth of fNIRS/mfNIRS is 1–2 cm (McCormick *et al.*, 1992; Quaresima and Ferrari, 2016; Torricelli *et al.*, 2014), whilst maintaining an optimal separation distance of approximately 3 cm between NIR light sources and detectors. The selection of the source-detector separation is dependent on the intensity of the NIR light (e.g. strength of sources) and the age and anatomical head properties of the participant (McCormick *et al.*, 1992; Quaresima and Ferrari, 2016; Torricelli *et al.*, 2014).

Given the penetration depth of on average 1–2 cm, mfNIRS allows marketing researchers to measure cortical brain regions that are *inter alia* associated with decision-making processes (Krampe *et al.*, 2018b), including the dorsolateral prefrontal cortex (dlPFC), the orbitofrontal cortex (OFC) and parts of the cortical ventromedial prefrontal cortex (vmPFC). It does not allow measurement of subcortical brain regions that are *inter alia* associated with affective information processing (Dalgleish, 2004) such as the anterior cingulate cortex (ACC), insula, nucleus accumbent or amygdala (Ernst *et al.*, 2013; Krampe, Gier *et al.*, 2018; Krampe *et al.*, 2018b). Researchers must therefore clarify in advance whether cortical brain regions and a marketing-relevant entity associated neuropsychological processes can be measured with mfNIRS. To this end, researchers can consolidate the neuroscientific open-source database www.neurosynth.org (Yarkoni *et al.*, 2011) (or other databases: www.open-neuroscience.com/en/), which provides information about the localisation of neuropsychological processes within the brain in a three-dimensional coordinate system arranged according to three axes of the human head, based fMRI data: the *x*-axis (left to right), the *y*-axis (posterior to anterior) and the *z*-axis (bottom to top). Marketing researchers who are particularly interested in cognitive and affective neuropsychological processes (e.g. cognitive load or perception processes associated with shopping-relevant cues or negotiation talks between value chain actors) must therefore be very precise when using MNI coordinates to examine whether a neuropsychological process and the associated brain region are indeed located near the surface of the human skull and can therefore be explored with mfNIRS. In addition, most marketing-relevant neuropsychological processes (e.g. decision-making processes) are known to integrate several brain regions (Broche-Pérez *et al.*, 2016) – a fact that the *neurosynth.org* database considers, indicating the connectivity of brain regions associated with a particular neuropsychological process or a brain region.

The "event-driven process chain" concerning *when* to apply mfNIRS can assist marketing researchers to decide whether mfNIRS is a valid and suitable neuroimaging method for investigate a marketing-relevant entity (Figure 2).

4.4 Potential confounding effects and possible solutions

Like most, *if not all*, scientific methods, mfNIRS systems must cope with several confounding influencing factors, which could have an impact on the measurement procedure and/or data quality. In particular, motion artefacts have been identified as influencing the collection – and therefore the quality – of mfNIRS data. In this regard, abrupt head and facial movements appear to be particularly influential when collecting mobile fNIRS data (Girouard *et al.*, 2010). To prevent head movement artefacts, researchers must

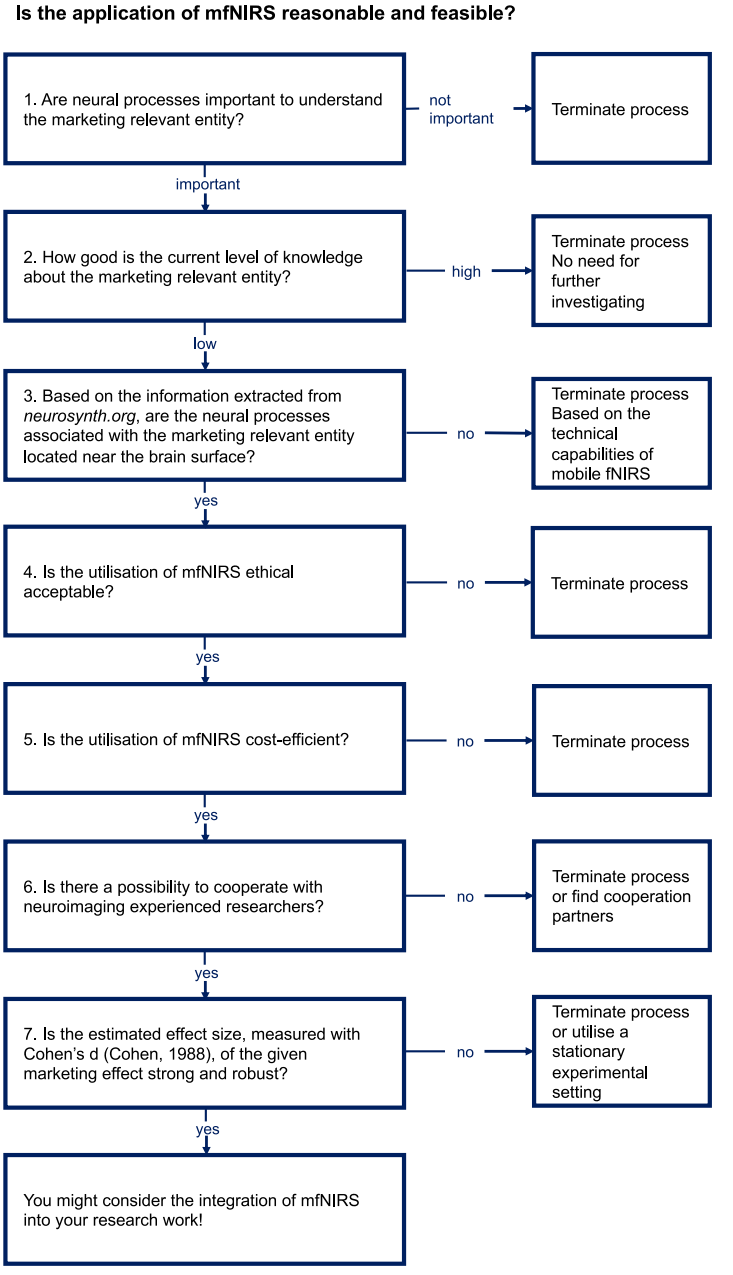

Figure 2.
Event-driven process chains for using mfNIRS

ensure that the headgear used has been correctly and stably placed on the participant's forehead. To do so, several steps are needed.

To correctly place the NIR light sources and detectors that cover the whole cortex or parts of the cortex, the 10–20 system (Jasper, 1958) is typically used in fNIRS studies to ensure that the cap or headband is placed accurately. As the 10–20 system uses data from the entire human cortex to determine the orientation of the NIR-light sources and detectors, this system is less suitable for positioning NIR light sources and detectors as integrated in the headband (Jasper, 1958). There are, however, several alternative solutions to place the headband. The mfNIRS headband can for example be locally standardised on the vertical axis using the craniometric point of the nasion as an orientation point and the middle of the two preauricular points for positioning the headband on the horizontal axis. In addition, the headband could also be placed on the frontal polar lines of the 10–20 system (León-Carrión *et al.*, 2010). Given the limited spatial resolution of mfNIRS, it should be evident that both of these placement procedures are indispensable to guaranteeing at least a minimum level of comparability between participants when analysing group-level data. Moreover, researchers must instruct participants to avoid strong, abrupt head movements. For measuring the cortical brain activity, innovative mfNIRS techniques that also integrate short channels (Brigadoi and Cooper, 2015) allow the simultaneous measurement of confounding signals (e.g. scalp blood circulation), thereby correcting the mfNIRS data as they are collected.

Given that ambient light might also be a cofounding variable, external light sources that might distort the mfNIRS signal during the measurement procedure need to be eliminated. Hence, to reduce the impact of environmental, external light, to assure an appropriate source-detector distance of about 3 cm and to guarantee sufficient light travelling through tissue, a proper skin contact with the NIR light sources and detectors have to be given. The resulting data quality can be checked by using an instrument-control software. Although data quality can be further evaluated and quantified later during offline data analysis, in many cases, it can be improved only within the limitations imposed by the quality of the raw data. Optimising the measurement setup is therefore of paramount importance. A range of software packages are available for data acquisition and analysis (e.g. Homer 3; NIRS Toolbox; AtlasViewer). Many are delivered along with fNIRS/mfNIRS devices or can be obtained online (e.g. https://nirx.net/software; www.nitrc.org/projects/homer2; https://openfnirs.org/software/homer/).

5. Applying mobile functional near-infrared spectroscopy in marketing research

5.1 Experimental procedure

To measure the neural processes and associated behaviour of customers in real-world situations – like at the point-of-sale or during negotiation talks – it is imperative to note that, to date, the environmental setting must be prepared to account and control for potential confounding environmental factors. Given the relative difficulty of identifying all occurrences of stimuli (e.g. unforeseen human interaction, background noise, functional pitfalls caused by movement-related artefacts) in naturalistic, mobile experiments, it is useful to combine mobile fNIRS with other neurophysiological methods, such as eye-tracking, to control for external, environmental cues whilst synchronising gaze directions and the neural mfNIRS data to be collected. Behavioural measurements should also be considered, as they allow for the interpretation of neural activity patterns measured through mfNIRS, in addition to hypotheses that are formulated according to theory. Given the necessity of such additional effort, and in the absence of innovative algorithms, the analysis of data from mfNIRS experiments currently requires significantly more time and effort, as

the stimuli onsets, *id est* the time that a stimulus occurred in the environment, must be defined *ex post*, using additional data sources. Moreover, because researchers cannot define the exact times at which stimuli occurred, the time series defined *ex post* might not be as accurate as the time series defined within a stationary experiment, which makes it possible to send a trigger signal at the exact time a stimulus occurs. Recent developments show that marketing researcher and practitioners can be supported in data analysis through the use of innovative algorithms and data analysis toolkits. Most of the offered packages include comprehensive manuals explaining how to use the toolkits and, consequently, to analyse fNIRS data. Given the variation in the application complexity of software packages, marketing researchers must draw on their experiences with neuroimaging methods to determine which software package to use. For example, toolkits that rely solely on MATLAB analysis software interfaces (ww2.mathworks.cn/en/products/matlab.html) might not be as user-friendly for novices as MATLAB-based toolkits that have already been integrated within the fNIRS/mfNIRS system (Figure 3).

5.2 Data pre-processing

Although the data analysis toolkits may differ in their user-friendliness, some general steps can be identified that are (more or less) valid for all procedures to analyse mfNIRS data. As a first step, the raw data (NIR light absorption rates) maybe pre-processed. The pre-processing of fNIRS data can be subdivided into three steps. In the first step, the signal quality of each mfNIRS channel (i.e. source–detector combination, as previously defined) is checked. In case of poor signal quality, e.g. due to light oversaturation or strong movement-related artefacts, the associated channel needs to be excluded from further analysis. It should be noted that this procedure inevitably results in the loss of data. Researchers should therefore be very careful about excluding channels and the data associated with them, and they should attempt to apply the aforementioned preventive measurements to increase the mfNIRS data quality. In a second step, discontinuities and movement (spike) artefacts from the data time series need to be eliminated. In addition, abnormalities with two or more adjacent channels that have *t-values* greater than three standard deviations from the group average (Fishburn *et al.*, 2014) or that indicate significantly more spike artefacts need to be

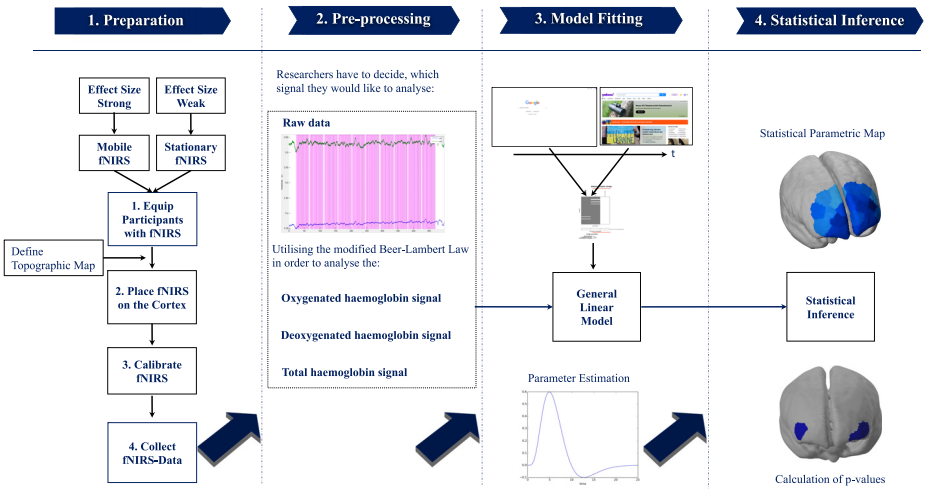

Figure 3.
Processual display of conducting mfNIRS experiments

excluded from further analysis. In this case as well, researchers should be very careful about the exclusion of data and, if applicable, such procedures should be reported.

In the final and third step of the pre-processing of mfNIRS data, a frequency filter can be used to smooth fNIRS data. In general, there are three different filter types that improve data quality based on individual data characteristics: low-, high- and band-pass filters. The low-pass filter deletes all fluctuations evolving over more rapid time scales from the data time series. This filter is often applied to de-noise data (removing aspects from the data that are not related to the measured effect). The high-pass filter deletes all fluctuations evolving over less rapid time scales. It is thus often used for de-trending (removing aspects of the data that is causing distortion). Lastly, the band-pass filter combines the low- and high-pass filters. It is particularly relevant when experimental events occur at regular time intervals, as is often the case in stationary mfNIRS experimental settings using a mixed-event/block design (Petersen and Dubis, 2012).

5.3 Data analysis

The analysis of oxygenated/de-oxygenated haemoglobin signals requires converting the pre-processed or raw NIR light absorption and attenuation data into concentrations of oxygenated and/or deoxygenated haemoglobin. Although previous research indicated significant correlations between fNIRS data signals and the sophisticated fMRI blood-oxygenation level-dependent (BOLD) signal (Noah *et al.*, 2015; Wijeakumar *et al.*, 2017), there is currently no consensus regarding whether the correlation is stronger with oxygenated haemoglobin (Hoshi *et al.*, 2001; Strangman *et al.*, 2002) or de-oxygenated haemoglobin signals (Huppert *et al.*, 2006; Toronov *et al.*, 2003), both of the signals that can be measured with mfNIRS. Recent literature concerning the validity and reliability of fNIRS/mfNIRS therefore suggests reporting both signals to avoid false positives (Hocke *et al.*, 2018; Tachtsidis and Scholkmann, 2016). The most commonly used algorithm to convert raw mfNIRS data into (de-)oxygenated haemoglobin signals is the modified Beer–Lambert law (Kocsis *et al.*, 2006; Kopton and Kenning, 2014; Scholkmann *et al.*, 2014). The Beer–Lampert law is defined by the following equation (Lloyd-Fox *et al.*, 2010):

$$\Delta A = \propto * \Delta c * L * DFC \tag{1}$$

It considers a constant optical scattering of the light and relates the change to the chromophore concentration (the smallest unit of light: photons) to changes in light attenuation (A), absorption coefficient (α), the concentration of the specific chromophore (c), source–detector separation (L) and the differential path length factor (DFC), all of which vary according to specific wavelengths, gender, age and differences in the tissue types (Kopton and Kenning, 2014; Lloyd-Fox *et al.*, 2010).

After the raw light absorption and attenuation data have been transformed into oxygenated/de-oxygenated haemoglobin concentrations, the following step consists of statistically analysing the haemodynamic-state time series at the within-session and/or within-subject level, or across multiple sessions or subjects. The standard approach involves fitting a general linear model (GLM) to each haemodynamic time series that has been defined *ex ante* (Kenning *et al.*, 2007). This model explains the response variable Yc (e.g. the haemodynamic response function at the smallest unit of the cortex surface, mostly pre-defined in a topographical layout, referred to as channel $c = 1, \ldots C$) in terms of a linear combination of the explanatory variables plus an error term:

$$Y_c = x_{c1}\beta_1 + \ldots + x_{cl}\beta_l + x_{cL}\beta_L + \varepsilon_c \tag{2}$$

Here, βl is the unknown parameter, corresponding to each of the L explanatory variables xcl (where $l = 1, \ldots L$). The error terms εc are independent.

Writing this equation in full for each channel c yields the following set of simultaneous equations:

$$Y_1 = x_{11}\beta_1 + \ldots + x_{1l}\beta_l + x_{1L}\beta_L + \varepsilon_1 \tag{3a}$$

$$Y_c = x_{c1}\beta_1 + \ldots + x_{c1}\beta_l + x_{cL}\beta_L + \varepsilon_c \tag{3b}$$

$$Y_C = x_{C1}\beta_1 + \ldots + x_{C1}\beta_l + x_{CL}\beta_L + \varepsilon_C \tag{3c}$$

It has the equivalent matrix form:

$$\begin{pmatrix} Y_1 \\ \cdots \\ Y_c \\ \cdots \\ Y_C \end{pmatrix} = \begin{pmatrix} x_{11} & \cdots & x_{1l} & \cdots & x_{1L} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{c1} & \cdots & x_{cl} & \cdots & x_{cL} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{C1} & \cdots & x_{Cl} & \cdots & x_{CL} \end{pmatrix} \begin{pmatrix} \beta_1 \\ \cdots \\ \beta_c \\ \cdots \\ \beta_C \end{pmatrix} + \begin{pmatrix} \varepsilon_1 \\ \cdots \\ \varepsilon_c \\ \cdots \\ \varepsilon_C \end{pmatrix} \tag{4}$$

and it can be written in matrix notation as follows:

$$Y = X\beta + \varepsilon \tag{5}$$

where Y is the column vector of observation, ε is the column vector of error terms and β is the column vector of parameters. The $C \times L$ matrix X with the cl^{th} element xcl is the design matrix. For example, this matrix can be used to specify the covariates corresponding to the different conditions in the experiment. If the participant repeatedly alternated between ten measurements of the experimental condition and ten of the control conditions, the model might include a covariate valued at 1 for each measurement corresponding to the control condition. After the design matrix has been defined, the different parameters are estimated based on the GLM (Kenning *et al.*, 2007). It should be noted that the design matrix is always dependent on the research questions. The regression coefficients associated with each covariate in the best fit are referred to as β values. They are used to compute statistical values (e.g. t or F) associated with each channel for a given contrast of covariates, as previously defined in a topographical map. The most common method to do so is the *contrast analysis*, in which various contrasts can be analysed in terms of the pre-defined experimental design and research questions (e.g. comparing the neural activity patterns of two different experimental settings, such as experimental versus control group). Once the contrasts have been defined and the statistics have been computed, neural activity differences can be displayed for every channel in a statistical parametric map: a brain image in which the value of each channel is its corresponding statistic. The significance p-value threshold should be defined according to the expected effect size (Cohens' d) (Cohen, 1988), and the results can be displayed in an anatomical representation of the brain. Most commonly, this consists of an atlas of the "standard brain": a computer-generated 3D model

derived from the brain anatomy of an individual or a group of subjects. In addition to contrast analyses, more advanced brain connectivity analyses that have recently been developed might be interesting in some situations, always depending on the research question (Hubert *et al.*, 2012; Zhang *et al.*, 2010; Lu *et al.*, 2010).

5.4 Data interpretation

To interpret the mfNIRS findings, marketing researchers and practitioners – who are assumed to have only limited knowledge of the anatomic structure of the human brain and the associated neuropsychological processes – can consult the open data approach of *neurosynth.org* (Yarkoni *et al.*, 2011) to acquire advanced knowledge on the specific research focus, the neuropsychological processes and its localisation and connectivity within the brain. One special feature of *neurosynth.org* is that it allows to identify all the research work that has been related to particular brain regions, research topics and/or cognitive constructs. This feature is of value as it automatically preselects the relevant literature, which might advance the consumer neuroscience and/or neuromarketing relevant knowledge of researchers and practitioners, helping them to interpret the mfNIRS related data and research findings.

6. Functional near-infrared spectroscopy/mobile functional near-infrared spectroscopy in marketing research: a status-quo analysis

To examine the current use of fNIRS/mfNIRS in marketing research, to assess *whether* and *how* the indicated guidelines are applied and to formulate theoretical and practical normative implications, a systematic review of recently published journal articles using mfNIRS/fNRIS experiments was conducted.

6.1 Applied methodology

The review was conducted according to a keyword search of "fNIRS", "marketing", "consumer neuroscience" and "neuromarketing" in the Google Scholar and Web of Science search engines (Martín-Martín *et al.*, 2021). The review includes only scientific journal articles concerning fNIRS/mfNIRS studies conducted from 2009 to 2021. It excludes, editorials, review articles, extended abstracts and conference submissions. Moreover, it focuses only journal articles published in the broader field of marketing research. This search procedure identified 13 articles using fNIRS/mfNIRS to answer marketing-relevant research questions.

The majority of the identified articles have focussed on validating fNIRS/mfNIRS in the field of consumer neuroscience (Kim *et al.*, 2016; Krampe *et al.*, 2018b; Liu *et al.*, 2018; Cakir *et al.*, 2018; Burns *et al.*, 2018), followed by studies using fNIRS/mfNIRS to predict the future consumer behaviour (Shimokawa *et al.*, 2009; Krampe *et al.*, 2018a; Cha *et al.*, 2019; Gier *et al.*, 2020; He *et al.*, 2021) and the exploration of cultural (Burns *et al.*, 2018) and/or gender-specific differences (Nissen and Krampe, 2021; Duan *et al.*, 2021). The scientific articles identified can, thus, be categorised according to four overarching themes in the use of fNIRS/mfNIRS: "validation" in marketing research, "behaviour prediction" based on neural cortical activity, exploration of "cultural differences" and evaluation of "gender differences". The results of the systematic literature review also reveal similarities and differences between the methodological approaches that have been used to conduct mfNIRS experiments (Figure 4).

No.	Year of publication	Type of article	Theme	Research aim	Brain regions covered	Signal measured	Number of sender and receiver used	Data-collection harmonisation methods applied	Correction for confounding effects	Combination with other neuroscientific methods	Results	Reference
1	2016	Research article	Validation	To verify the application of fNIRS/mfNIRS to predict consumer food choices	Prefrontal cortex	Oxygenated haemoglobin level	8x8 (no full coverage of PFC)	⊗	✓	⊗	Significantly increased neural activity occurred in the right prefrontal cortex area when less-preferred food images were presented compared to when preferred food images were presented.	Kim, Kin, Han, Lim and Im (2016)
2	2018	Research article	Validation	To validate fNIRS in the consumer neuroscience research and neuromarketing, replication a robust, well-investigated neural effect: the first-choice brand effect.	Dorsolateral prefrontal cortex	Oxygenated haemoglobin level	8x8 (no full coverage of PFC)	✓ and ⊗	✓	⊗	mfNIRS appears to be an appropriate neuroimaging method for research in the fields of neuromarketing and consumer neuroscience research.	Krampe, Gier and Kenning (2018)
3	2018	Research article	Validation	To use fNIRS/mfNIRS to investigate consumer to distinguish positive and negative visual-merchandising displays in fashion stores, based on neural activity	Prefrontal cortex	Oxygenated haemoglobin level	4x10 (no full coverage of PFC)	✓	?	⊗	fNIRS/mfNIRS can be used to measure the neural brain activation involved in the evaluation of fashion-store displays.	Liu, Kim and Hong (2018)
4	2018	Research article	Validation	To explore the plausibility of fNIRS for neuromarketing and develop a neuro-physiologically-informed mode of purchasing behaviour.	Fronto-polar brain regions (closely related to orbitofrontal cortex and ventro-medial prefrontal cortex	Oxygenated haemoglobin level	8x8 (no full coverage of PFC)	⊗	✓	⊗	Neural activity measured with fNIRS can be used to decode the 'buy or pass' decision with 86% accuracy.	Cakir, Çakar, Girisken and Yurdakul (2018)*
5	2018	Research article	Validation	To replicate fMRI findings, exploring neural activity patterns during the	Medial prefrontal cortex and dorsolateral	Oxygenated and de-oxygenated	Not indicated (but no full coverage of PFC)	✓ and ⊗	✓	⊗	The results are consistent with fMRI findings, indicating significant neural activity associated with message-	Burns, Barnes, Katzman, Ames, Falk and
				'sunscreen persuasion paradigm' to predict behavioural change, utilising mfNIRS.	prefrontal cortex	haemoglobin level					consistent behaviour change, above and beyond self-reported intentions.	Lieberman (2018)
6	2009	Research article	Behaviour prediction	To examine the neural correlates associated with reward prediction and risk prediction as part of decision-making under risk.	Medial prefrontal cortex and orbitofrontal cortex	Oxygenated and de-oxygenated haemoglobin level	10x10 (no full coverage of PFC)	✓ and ⊗	✓	⊗	Neural activity changes include information for the effective prediction of investment behaviour.	Shimokawa, Suzuki, Misawa and Miyagawa (2009)
7	2018	Research article	Behaviour prediction	To examine the neural reactions of consumers to different merchandising communication strategies at the PoS.	Prefrontal cortex, dorsolateral prefrontal cortex, and orbitofrontal cortex	Oxygenated haemoglobin level	8x8 (no full coverage of PFC)	✓ and ⊗	✓	⊗	mfNIRS appears valid method for studying neural activity in the prefrontal cortex in the field of shopper neuroscience, demonstrating that the orbitofrontal cortex can act as a process variable for predicting the effectiveness of merchandising communication.	Krampe, Strelow, Haas and Kenning (2018)*
8	2019	Research article	Behaviour prediction	To determine the auditory-sensory characteristics of digital pop music that is particularly successful on YouTube.	Right medial prefrontal cortex	Oxygenated and total haemoglobin level	3x7 (no full coverage of PFC)	✓	?	⊗	Activity in brain regions of the right medial prefrontal cortex increased when young adults heard music that presented acoustic stimulation well above previously defined optimal sensory level.	Cha, Suh, Kwon, Yang and Lee (2019)
9	2020	Research article	Behaviour prediction	To predict the success of PoS-merchandising elements on sales, using neural activity patterns measured with fNIRS/mfNIRS.	Dorsolateral brain regions	Oxygenated haemoglobin level	8x8 (no full coverage of PFC)	✓	✓	⊗	The neural signals of brain regions of the dlPFC (measured with mfNIRS) can predict actual sales associated with PoS-merchandising elements.	Gier, Strelow and Krampe (2020)
10	2021	Research article	Behaviour prediction	To investigate the neural correlates of empathy and emotional contagion, when perceiving advertisements.	Right inferior frontal gyrus	Oxygenated haemoglobin level	6x6 (no full coverage of PFC)	✓ and ⊗	✓	⊗	The neural correlates suggest that mfNIRS can predict attitudes towards advertisements, measuring brain regions ascribed to empathy and emotional contagion.	He, Pelowski, Yu and Liu (2021)
11	2018	Research article	Culture differences	To explore whether persuasive stimuli expose the same neural activity pattern in different cultural environments.	Dorsolateral prefrontal cortex and ventromedial prefrontal cortex	Oxygenated haemoglobin level	8x8 (no full coverage of the PFC)	✓	?	⊗	Neural activity in the dorsolateral prefrontal cortex and ventromedial prefrontal cortex predicted how persuasive participants found the stimuli and how much they intended to engage in the behaviours endorsed in the message.	Burns, Barnes, McCulloh, Dagher, Falk, Storey and Lieberman (2019)
12	2021	Research article	Gender differences	To explore gender differences in e-commerce, applying traditional marketing methods and fNIRS/mfNIRS.	Prefrontal cortex	Oxygenated and de-oxygenated haemoglobin level	8x8 (no full coverage of the PFC)	✓	✓	⊗	The results revealed no gender difference in self-reported evaluations of e-commerce websites but indicated differences in the neural activity patterns of women and men.	Nissen and Krampe (2021)
13	2021	Research article	Gender differences	To explore the neural correlated of gender specific purchase decisions on different cross-cultural marketing strategies.	Dorsolateral prefrontal cortex & medial prefrontal cortex	Oxygenated and de-oxygenated haemoglobin level	16x16 (no full coverage of the PFC)	✓	✓	⊗	The results revealed that female participants show higher purchase rates for original culture advertisements and an increased neural activity in the left dlPFC when exposed to mixed culture advertisements; effects that were not found for male participants.	Duan, Ai, Yang, Xu and Xu (2021)

Figure 4.
Recent fNIRS/mfNIRS experiments in the fields of consumer neuroscience and neuromarketing

Notes: * Both studies were published in the EJM special issue on neuromarketing that was guest-edited by Daugherty and Thomas (2018)

6.2 Application-oriented commonalities

The results of the systematic literature review indicate that the mfNIRS headband is the most commonly used device for measuring brain activity patterns of the prefrontal cortex within the field of marketing research. The focus on brain regions ascribed to the prefrontal cortex is supported by recent research (Carlén, 2017), indicating three central brain regions that are known to play an essential role in explaining marketing-relevant entities. Firstly, the dlPFC has been investigated in many studies (Harris *et al.*, 2018; Lim, 2018; Gier *et al.*, 2020). The results obtained from these investigations include the finding that complex cognitive perceptions and decision-making processes can be associated with the dlPFC (Deppe *et al.*, 2005; Knutson *et al.*, 2007; Krampe *et al.*, 2018b). Secondly, the OFC has been identified as an essential brain region. It has been related to decision-making processes and marketing-relevant entities, including the willingness to pay or the "liking" of objects, products, or advertising activities (Kühn *et al.*, 2016; Plassmann *et al.*, 2008; Wallis, 2007; Krampe *et al.*, 2018a). Third, the medial/ventro-medial cortex continues to be of crucial importance in consumer neuroscience and neuromarketing research and has been linked to neuropsychological processes that underly individual value refraction and self-control in decision-making (Deppe *et al.*, 2005; Hare *et al.*, 2009).

The overarching role of the prefrontal cortex in consumer neuroscience and neuromarketing research should therefore be evident, explaining the research focus of recent mfNIRS studies. It is nevertheless important to note that other sub-cortical brain regions – such as the nucleus accumbens, which is generally associated with reward aspects (Knutson *et al.*, 2007); the amygdala, which is associated with emotional/affective processing (Sergerie *et al.*, 2008); and the ACC, which integrates cognitive processes of conflict recognition and conflict resolution (Kerns *et al.*, 2004) – are also essential to the study of marketing-relevant entities. To date, however, technological limitations have prevented the exploration of these brain regions with mfNIRS, stressing again the importance to consider in advance whether mfNIRS can be used to answer specific research questions, given the correlation of the construct of interest and the associated brain regions (Figure 2).

Another interesting finding of the systematic literature review is that most fNIRS/mfNIRS studies concentrated primarily on oxygenated haemoglobin levels. As indicated before, there is an ongoing discussion concerning whether the oxygenated, de-oxygenated or total haemoglobin level is the best predictor of cortical neural activity (Dravida *et al.*, 2017). Following this discussion and the associated mixed research findings, both haemoglobin levels might be reported in future studies, or if chosen for one, it should be explained – in terms of the research questions and the fNIRS/mfNIRS system to be used – which signals are analysed and why. In addition, haemodynamic signals might be improved with anti-correlation methods or by integrating short channels to the mfNIRS headband or cap (Zhou *et al.*, 2020).

In the majority of the fNIRS/mfNIRS studies reported, data collection is harmonised by using *one* particular data collection procedure. Some studies use the 10–20 system (Jesper, 1958), while others use a more applied methodological approach (focussing on the nasion and/or the two preauricular points) (Figure 4). The 10–20 system appears particularly suitable for full-head measurement procedures using a whole-head cap. This observation is only conditionally valid for the studies reviewed, as they are based on data collected with a headband, and not with a cap covering the whole cortex. To date, there does not appear to be any single, accepted method for harmonising mfNIRS data collection. Such an approach is, however, needed as it could help to set standards, thereby allowing the comparison of marketing-relevant mfNIRS research findings across neuromarketing or consumer neuroscience studies. To ensure a minimum of comparability, when using the headband to measure brain regions of the prefrontal cortex, the craniometric point of the nasion can be used as a landmark

on the vertical axis, and the middle of the two preauricular points can be used to position the headband on the horizontal axis to ensure that the same standardisation is used in all mfNIRS experiments in the future.

Most of the fNIRS/mfNIRS studies reviewed apply preventive and/or post-experiment data correction methods to cope for confounding effects, such as external light sources or abrupt head movements. These preventive applications are essential to increasing the quality of mfNIRS data, and they need to be considered in future research by applying preventive and post-data correction methods.

Although the combination of mfNIRS with other neuroscientific methods (defined as non-neuroimaging methods, like eye-tracking, pupillometry, electrocardiogram or heart rate variability) appears to be useful (Venkatraman *et al.*, 2015), none of the studies reviewed attempts to combine mfNIRS with other neuroscientific methods and tools. The combination of mfNIRS with existing (neuroimaging) methods, acting as control elements to manage potential confounding effects that occur in a naturalistic research environment, might therefore increase the explained variance when investigating marketing-relevant entities. Future research in consumer neuroscience and neuromarketing might therefore explore the possibility of combining mfNIRS with other neuroscientific methods taking software and hardware issues into account, further validating mfNIRS in marketing research.

6.3 Research-oriented commonalities

As with any emerging methodology, it remains imperative to validate mfNIRS in the field of marketing research. To this end, the vast majority of the studies reviewed use multiple approaches to validate mfNIRS in marketing research. In general, four validation approaches may be used to validate a neuroimaging method in marketing research (Krampe *et al.*, 2018a):

(1) *Predictive validity*, which is given when a measurement accurately predicts behaviour according to theory;

(2) *Construct validity*, which requires measurements obtained from a measurement procedure to behave exactly the same as the actual variable;

(3) *Divergent validity*, which is demonstrated when two different methods measure two different constructs without revealing any relationship; and

(4) *Convergent validity*, which is given when a strong relationship is found between the scores obtained from two different methods measuring the same construct (Gravetter and Fozano, 2018).

The results of the systematic review show that two of the four validity approaches have been used to validating mfNIRS in marketing research.

Following the *predictive validity approach*, Kim *et al.* (2018) report on a fNIRS study in which participants were requested to evaluate food images whilst wearing a mfNIRS headband. The results show that fNIRS is capable of predicting whether participants will favour or reject food images, based on increased neural activity in the right prefrontal cortex. Studies by Liu *et al.* (2018) and Cakir *et al.* (2018) add to these findings by showing that using fNIRS/mfNIRS to measure neural brain activity is helpful in merchandising activity evaluation and examining the related decision-making processes. Just recently, He *et al.* (2021) indicated further that mfNIRS is capable of exploring the neural correlates, which can predict attitudes towards advertisements, measuring brain regions of the right inferior frontal gyrus, which is ascribed to empathy and emotional contagion.

In addition, studies by Burns *et al.* (2018) and Krampe *et al.* (2017) adopt a convergent validity approach to validate the use of mfNIRS in marketing research. Both studies

replicate a frequently cited neural effect that has previously been explored with fMRI to determine whether mfNIRS is capable of replicating fMRI results, given its technical capabilities. The results are consistent with previous fMRI findings, indicating significant neural activity in brain regions ascribed to specific neural and marketing-relevant effects.

It should, however, be mentioned that the indicated studies only targeted research questions that can be attributed to B2C marketing settings – more specifically to the field of consumer neuroscience. Though, B2C and B2B companies are different, both are confronted with dynamic changing market environments to which they need to respond (Lim *et al.*, 2019). Future research might therefore approach the validation of mfNIRS also in a B2B marketing setting (Lim, 2018), focussing on research questions that examine *inter alia* interactions between actors of the value chain. Aspects that would contribute to the further validation of mfNIRS in the field of marketing research, as a whole.

mfNIRS has also been applied to predict consumer behaviour. More precisely, the neural activity elicited by marketing-relevant stimuli (e.g. auditory-sensory characteristics of a video sequence or point of sale merchandising elements) have been linked to behavioural/sales data to predict actual purchasing or consumption behaviour (Krampe *et al.*, 2017; Cha *et al.*, 2019; Gier *et al.*, 2020). Moreover, mfNIRS has been applied to predict decision-making under risk and to explore information to predict investment behaviour (Shimokawa *et al.*, 2009). The advantage of using mfNRS in real-world environments to predict customer behaviour adds value to marketing research, as it opens up the possibility of validating research findings that have been studied in an artificial laboratory environment. The application of mfNIRS could therefore strengthen future research approaches by allowing a marketing-relevant entity to be explored through different real-world perspectives focusing on neuropsychological, behavioural and traditional marketing methods insights in a real-world setting. Also, mfNIRS has recently been used to explore cultural and/or gender-specific differences in perceptions of persuasive messages (Burns *et al.*, 2019), e-commerce websites (Nissen and Krampe, 2021) or in transnational brand purchase decisions associated with original or mixed culture advertisements (Duan *et al.*, 2021). Aspects that provide additional evidence of the ability of mfNIRS to investigate individual differences between customers throughout the entire online and offline value chain.

7. Conclusion

The presented guidelines for the use of mfNIRS show that the methodological issues and performance of mfNIRS are relatively high for newcomers to the field of consumer neuroscience and neuromarketing. However, compared to other neuroimaging methods, such as fMRI, mfNIRS is less costly and can be applied in naturalistic contexts – two arguably fundamental factors in marketing research. As outlined in the review of recently published fNIRS/mfNIRS studies in marketing research, the application of mfNIRS in marketing has the potential to fundamentally improve the understanding of marketing-relevant entities by increasing the ecological validity in B2C and B2B marketing settings. However, the latter requires future research efforts with the aim of validating mfNIRS as a neuroimaging method also in the B2B context. Researchers and marketers are therefore advised to broaden the scope of mfNIRS research to include the study of (neural) exchange processes between actors in the value chain. This offers opportunities to explore marketing-relevant entities in their entirety, which advances marketing research as a whole and which goes beyond the previous investigation of impact-oriented research approaches. The presented guidelines support this development by proposing harmonised standards and procedures for the application of mfNIRS in marketing research that enable comparability between research findings.

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