NEUROMETRICS APPLIED TO BANKNOTE AND SECURITY FEATURES DESIGN

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Abstract

The aim of this paper is to present a methodology on the application of neuroanalysis to the design of banknotes and security features. Traditionally, evaluation of the perception of banknotes is based on explicit personal responses obtained through questionnaires and interviews. The implicit measures refer to methods and techniques capable of capturing people's implicit mental processes. Neuroscience has shown that, in most brain processes regulating emotions, attitudes, behaviours and decisions, human consciousness does not intervene. That is to say, these implicit processes are brain functions that occur automatically and without conscious control.

The methodology on neuroanalysis can be applied to the design of banknotes and security features, and used as an effective analysis tool to assess people's cognitive processes, namely: visual interest, attention to certain areas of the banknote, emotions, motivation and the mental load to understand the design and level of stimulation. The proposed neuroanalysis methodology offers a criterion for making decisions about which banknote designs and security features have a more suitable configuration for the public. It is based on the monitoring of conscious processes, using traditional explicit measures, and unconscious processes, using neurometric techniques.

The neuroanalysis methodology processes quantifiable neurometric variables obtained from the public when processing events, such as eye movement, sight fixation, facial expression, heart rate variation, skin conductance, etc. A neuroanalysis study is performed with a selected group of people representative of the population for which the design of a banknote or security features is made. In the neurometric study, suitably prepared physical samples are shown to the participants to collect their different neurometric responses, which are then processed to draw conclusions.

Keywords: neuroscience, eye tracking, biometrics, neurometrics, banknotes, neurodesign, security feature, perception, human behaviour.

JEL classification: C13, D87, E42.

UNESCO classification:

- 530406 Money and banking
- 610609 Perception processes
- 611406 Consumer behavior
- 630201 Field data collection
- 630203 Social survey design
- 630204 Social survey methods
- 630501 Measure and index construction
- 630502 Model building
- 630503 Statistical analysis

Resumen

El objetivo de este trabajo es presentar una metodología sobre la aplicación del neuroanálisis en el diseño de billetes y elementos de seguridad. Tradicionalmente, la evaluación de la percepción de los billetes se ha basado en respuestas explícitas de las personas, obtenidas a través de cuestionarios y entrevistas. Las medidas implícitas se refieren a métodos y técnicas capaces de capturar los procesos mentales implícitos de las personas. La neurociencia ha demostrado que la consciencia humana no interviene en la mayoría de los procesos cerebrales que regulan las emociones, actitudes, comportamientos y decisiones. Es decir, estos procesos implícitos son funciones cerebrales que se producen automáticamente y sin control consciente.

La metodología sobre el neuroanálisis puede aplicarse al diseño de billetes y elementos de seguridad, y utilizarse como una herramienta de análisis eficaz para evaluar los procesos cognitivos de las personas, como el interés visual, la atención a ciertas áreas del billete, las emociones, la motivación, la carga mental para comprender el diseño y el nivel de estimulación. La metodología del neuroanálisis propuesta ofrece un criterio para tomar decisiones sobre qué diseños de billetes y elementos de seguridad tienen una configuración más adecuada para el público, basada en el seguimiento de procesos conscientes, usando medidas explícitas tradicionales, y procesos inconscientes, usando técnicas neurométricas.

La metodología del neuroanálisis trata variables neurométricas cuantificables obtenidas del público al procesar eventos como el movimiento ocular, la fijación visual, la expresión facial, la variación del ritmo cardíaco, la conductancia de la piel, etc. La aplicación de un estudio de neuroanálisis se lleva a cabo con un grupo de personas representativo de la población para la que se realiza el diseño de un billete o los elementos de seguridad. En el estudio neurométrico se ofrece a los participantes muestras físicas adecuadamente preparadas para recoger las diferentes respuestas neurométricas de los participantes, que luego se procesan para sacar conclusiones.

Palabras clave: neurociencia, seguimiento ocular, biometría, neurometría, billetes de banco, neurodiseño, elemento de seguridad, percepción, comportamiento humano.

Códigos JEL: C13, D87, E42.

Códigos Unesco:

- 530406 Dinero y operaciones bancarias
- 610609 Procesos de percepción
- 611406 Comportamiento del consumidor
- 630201 Recogida de datos de campo
- 630203 Diseño de investigación social
- 630204 Métodos de investigación social
- 630501 Media y construcción de índices
- 630502 Elaboración de modelos
- 630503 Análisis estadístico

Index

1 Introduction

People handle cash almost every day of their life. Therefore, it is important that banknote design should be aesthetic and functional, with eye-catching security features accommodating the requirements of all users and banknote-accepting devices. Central banks pay great attention to this aspect in order to safeguard the integrity and functionality of their currency, and public confidence in it. Furthermore, we live in a world of visual stimuli; hence, banknotes must take into account the intellectual and emotional processes of the public. Also, the functional aspects of banknotes must provide for their ready recognition, for detection of their rigorous authenticity and for simple handling. Therefore, knowing how people perceive the design of banknotes and their security features is crucial for central banks. This is specifically our commitment with this paper, which paves the way for banknote neurodesign, a methodology based on neuroscience techniques that measure the behaviour of the participants. Neurodesign provides several signals called neurometrics, i.e. the metrics provided by various measurement techniques based on the biometric response of human beings, such as those mentioned in Section 3. The neurodesign methodology will, therefore, contribute to enhancing decision-making in banknote design through a rigorous scientific procedure, by means of which the public's perception of the graphic design and security features of a banknote may be objectively obtained. This methodology is able to evaluate stimuli on aesthetic and cultural aspects, the substrate, the sense of security and the transmission of values that a banknote produces in people.

Specifically, the paper aims to provide a new methodology for the design and security features of banknotes that validates and quantifies the effectiveness of using new neurometric techniques to help central banks and issuing authorities better understand how the general public perceives banknotes. To do this, a new methodology encompassing all knowledge about the development of banknotes and the attendant graphic language, security technology and neuroscience techniques has been developed in order to obtain an unbiased public perception on the design of banknotes and their security features. Use has been made of the latest neuroscience techniques and the measurement of how people respond to a representative worldwide banknote sample. Parsing several physiological responses along with the subjects' conscious assessment while they feel, look at and tilt banknotes, patterns in unconscious responses for different banknote designs and potential correlations between the neurometrics obtained and the final design evaluation have been explored in order to be able to establish a new neurometric banknote design methodology.

The knowledge employed in this article takes into account banknote design, public perception and public security features. In that way, the methodology presented on the basis of neuroscience is a novel contribution in the field of banknote design and security features evaluation.

2 Neurometrics in perception studies

Neuroimaging and physiological measurement tools are becoming popular in perception studies. Their primary uses are related to unconscious measures based on eye movement, facial expression, heart rate and brain activity, among others (Venkatraman *et al.* (2015)). These tools aim to provide for a better understanding of the impact of affect and cognition on memory (Vecchiato *et al.* (2014)). Neurophysiological methods offer richer data than self-reported measurements of particular interest in product perception research. Firstly, physiological measurements of emotion allow researchers to analyse emotional activity without cognitive bias. Secondly, neurophysiological methods provide instant and continuous data that allow researchers to decompose the data analysis into small pieces for study. Lastly, physiological measurements typically offer a myriad of quantitative metrics that can be correlated with insights of interest in every study.

Understanding how people come to their decisions is a scientific area that is receiving a lot of attention. There are several theories that try to explain how people make decisions, and what types of factors influence them. According to Panksepp (2005), advances in human neuroscience have led to an understanding that certain brain areas are involved in both “cold” and “hot” cognitive decision-making processes. Panksepp has found support for this view in the work with functional Magnetic Resonance Imaging (fMRI) by Goel *et al.* (2003) for examining the neuronal basis of emotionally neutral (“cold”) and affectively striking (“hot”) reasoning. These studies have demonstrated the existence of a dynamic neuronal system for the processing of dorsolateral prefrontal cortex (dlPFC) information for “cold” processing and of ventromedial prefrontal cortex (vmPFC) information for “hot” processing. In human affective neuroscience, the cold-hot dual processing approach is widely accepted by the neuroscientific community (Bechara *et al.* (2005) and Greene *et al.* (2001)).

Underlining the importance of “hot” processes, it is easy to believe that there is more in people’s minds than they say. This disunity illustrates the compelling quality of introspective experience. To own the mind is a privileged position: to have exclusive access to the conscious experience and the sure feeling that the mind and one’s own experience refer to the same thing. However, mental experience is not the same as mental operations. One’s beliefs about why a behaviour was performed need not to be related to its actual cause, and people’s reports on the causes of their decisions can be reliably but incorrectly asserted simultaneously (Nisbett *et al.* (1977)). Greenwald *et al.* (1995) introduced the term “implicit social cognition” to describe cognitive processes that occur outside consciousness or conscious control in relation to social psychological constructs: attitudes, stereotypes and concepts of oneself.

Traditionally, most human decision-making theories are based on a model of the human mind which assumes that humans can deliberately and accurately verbalise their attitudes, emotions and behaviours (Brief (1998)). Thus, to date, most theoretical constructs are based on explicit measures such as questionnaires and interviews.

However, recent advances in neuroscience are proving that most of the brain processes that regulate our emotions, attitudes, behaviours and decisions are out of our consciousness. Implicit processes are brain functions that occur automatically and out of conscious control and awareness; in contrast, explicit processes occur through conscious executive control (Becker *et al.* (2011)). This paper will define implicit measures as any method of investigation and / or technique capable of capturing or tracking implicit brain processes or their results, including brain images, behavioural monitoring and psychosomatic results. In contrast, explicit measures refer to techniques, such as questionnaires, self-reports or interviews, in which the person must make an explicit process to verbalise the results of implicit processes.

Explicit measures have been shown to be conditioned by "social desirability effects", which can lead to false accounts of behaviours, attitudes and beliefs (Paulhus (1991)). Secondly, there may be different interpretations of specific self-report elements, resulting in less reliability and less validity (Lanyon *et al.* (1997)). Third, some self-reported questions require people to have open knowledge of their dispositions (Schmitt (1994)), and this is not always the case.

Recent studies have been demonstrating the considerable influence of implicit processes on psychological constructs and neurocognitive mechanisms of special relevance for humans, such as attitudes (Fazio *et al.* (1999)), stereotypes (Nosek *et al.* (2002)), self-confidence (Krause *et al.* (2016)), personal relationships (Banse (1999)), decision-making (Bagozzi (2014)) and personal attachment (Chicchi Giglioli (2017)).

The importance of considering the implicit measures to improve the knowledge of decision-making in different contexts has given rise to new scientific disciplines in each such context such as neuroeconomics (Glimcher (2003)), labour relations in the workplace (Waldmans *et al.* (2015)), leadership (Raya *et al.* (2018)), marketing (Guixeres *et al.* (2017)) and occupational risk (Diego-Más (2014)).

In the great majority of these works, only explicit measures of implicit processes have been used, with the aforementioned limitations this entails.

There is a recent growing interest within the scientific community about the development of techniques of implicit measures for implicit brain processes that obviate the use of explicit measures. The different techniques employed are based on measurements that in turn are related to some implicit process. These techniques vary both in the specificity of the implicit process to which they are related and in spatial and temporal resolution. The implicit measures used so far are based on brain, physiological and imaging techniques such as functional magnetic resonance imaging (fMRI) (Cunningham *et al.* (2004)), near infrared spectroscopy (fNIRS) (Kopton *et al.* (2014)), electro dermal activity (EDA) (Nikula (1991)), electroencephalography (EEG) (Knyazev *et al.* (2009) and Rodríguez *et al.* (2015)), and eye tracking (ET) (Amodio *et al.* (2003) and heart rate variability (HRV) (Lane (2008)), among others. What these various approaches have in common is that they all seek to provide an estimate of the construct of interest without having to request the verbal report directly from the participant. The main attraction is that these indirect estimates are probably free of concerns of social desirability. While not necessarily true for all measures, the participant often does not know that attitudes, stereotypes, etc. are not being evaluated.

It should be emphasized that this is not to say that implicit process measures invalidate results and constructs modelled from explicit processes. On the contrary, it is argued that the current theories and methods of human decisions are incomplete, and sometimes inaccurate, because they are biased by data coming solely and exclusively from explicit process measures. Therefore, implicit measures will be a necessary component of any research activity regarding human decisions, including human perception evaluation.

In this case, following the Coaster model (De Heij (2015)), the study will focus on analysing whether the use of new metrics from the biometric measurement of humans can provide a more efficient and quantitative way of evaluating user experience functions (UXFs) and user interface (UIFs) regarding banknote perception. Humans have been demonstrated to have a capacity one hundred thousand times greater for processing unconscious as opposed to conscious information. Unconscious responses cannot be measured if the value information comes exclusively from voluntary responses of the persons who have been most involved in the few studies of banknote perception existing at present (Masuda *et al.* (2015), Shao *et al.* (2016) and Klein *et al.* (2004)).

It is therefore a clear objective of the paper to validate a new citizen banknote perception methodology through the use of the latest measures and techniques of behaviour measurement in neuroscience to be used for banknote and security feature design. This will allow a series of "banknote metrics" to be established when characterising the current perception of different banknote design and security features. Subsequently, it will be possible to study any difference between banknotes or groups that contributes more quantitative measures and greater sensitivity. Comparison between banknotes enables them to be accurately ordered, especially in a big list of banknotes as in this case (18 banknotes). It would be very difficult for somebody to voluntarily have the sensitivity to be able to consistently order this number of banknotes. Being able to compare across groups allows for quantification of whether, statistically, there are differences in the perception of the banknote, including anthropometric population factors such as gender or age, or factors related to the handling of money, as is the case for people working in an environment where banknotes are handled or not. Another case is the comparison, as in this paper, of whether training has had an effect on the results obtained when visually perceiving the banknote.

3 Neurometric methodology

3.1 Fundamentals

Neuroscience and, more specifically, measurement techniques based on the biometric response of humans have improved a lot in recent years, allowing for their use in studies of valuation of products, digital contents and even in real spaces (Piqueras-Fiszman *et al.* (2013), Milosavljevic *et al.* (2012), Rebollar *et al.* (2015) and Spence *et al.* (2014)). In this case, as banknotes can be considered a product and a design element, these neuroscientific techniques can be also applied to banknote perception and design.

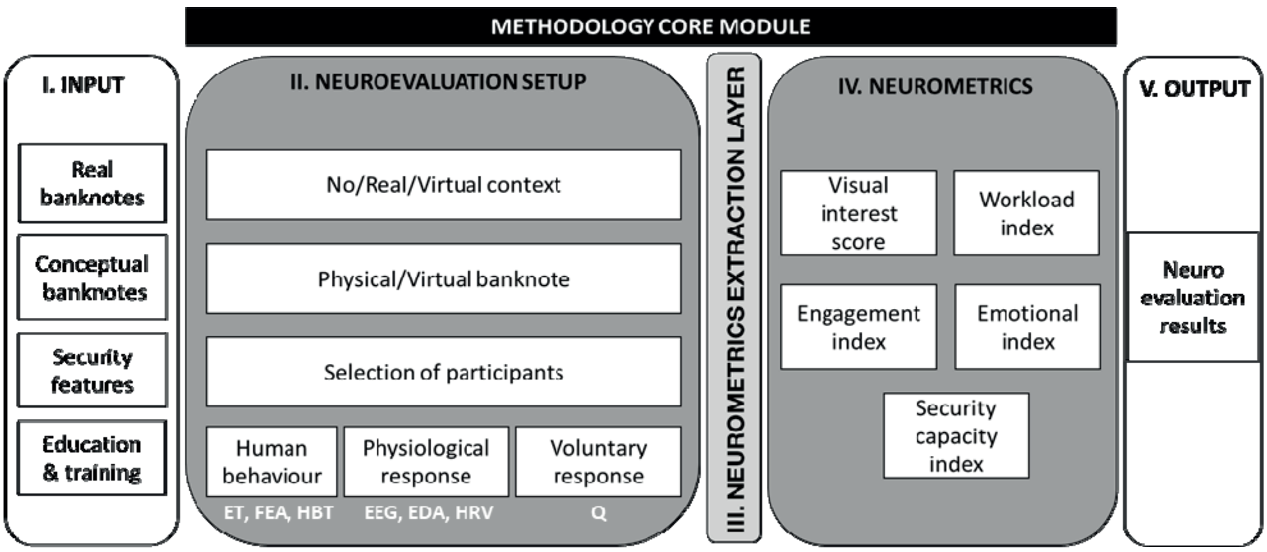
The methodology is composed of a series of input signals: $x^i = \left[x_1^i, x_2^i, \cdots, x_n^i\right]$ over which operates a set of algorithms $f_{i,j}$ to condition and extract the neurometrics related to the perception of the banknote: $x^0 = \left[x_1^0, x_2^0, \cdots, x_m^0\right]$.

In a matrix form, it is: $x^0 = A \cdot x^i$, with $A \in M_{m \times n}(R)$ being the neurometric matrix of banknotes.

$$A = \begin{bmatrix} f_{1,1} & \cdots & f_{1,n} \\ \vdots & \ddots & \vdots \\ f_{m,1} & \cdots & f_{m,n} \end{bmatrix}$$

which agglutinates the set of operations performed in the neurometric processing layer described in Figure 1.

Figure 1
NEUROMETRIC METHODOLOGY GENERAL SCHEME



SOURCES: Banco de España and LENI.

Table 1
NEUROMETRICS MEASUREMENT CHART

	Signals	What is measured?	How is it measured?	Which metrics can be derived?	How can the data be interpreted?
Human behaviour	ET (eye tracking)	Corneal reflection & pupil dilation	Infrared cameras point towards eyes	Eye movements (gaze, fixation, saccades), blinks, pupil dilation	Visual attention, engagement, drowsiness & fatigue, emotional arousal
	FEA (facial expression analysis)	Activity of facial muscles	Camera points towards face	Position and orientation of head. Activation of action units (aus) Emotion channels	Emotional valence, engagement, congruency of self-reports
	HBT (human behaviour tracking)	Analysis of gestures	Camera points towards hands	Hands movement, manipulation of the banknote	Behaviour, engagement and emotional activity
Physiological response	EEG (electroencephalogram)	Changes in electrical activity of the brain	Electrodes placed on scalp	Frequency band power, frontal lateralisation, event-related potentials, wavelets	Attention, emotional arousal, motivation, cognitive states, mental workload, drowsiness & fatigue
	EDA (electro dermal activity)	Changes in skin conductance	Electrodes attached to fingers, palms or soles	Skin conductance response (SCR)	Emotional arousal, engagement, congruency of self-reports
	HRV (heart rate variability)	Variability in heart contraction intervals	Electrodes attached to chest or limbs or optical sensor attached to finger, toe or earlobe	Heart rate (hr). Interbeat interval (ibi). Heart rate variability (hrv)	Emotional arousal, stress, physiological activity

SOURCE: LENI.

Within the scope of this type of study, the main measured neurometric signals are those shown in Table 1, which describes how they are measured, and which insights can be obtained from each signal.

3.2 Selection of a representative banknote sample for the study

The worldwide banknotes considered for the study are listed in Table 2, comprising those both in and out of circulation and manufacturer sample banknotes. These banknotes have been selected as a representation of the different designs and security features present in banknotes around the world. With this selection, banknotes from all the continents are covered, printed on different substrates (paper, polymer or hybrid)

Table 2

LIST OF WORLDWIDE BANKNOTES EVALUATED IN THE STUDY

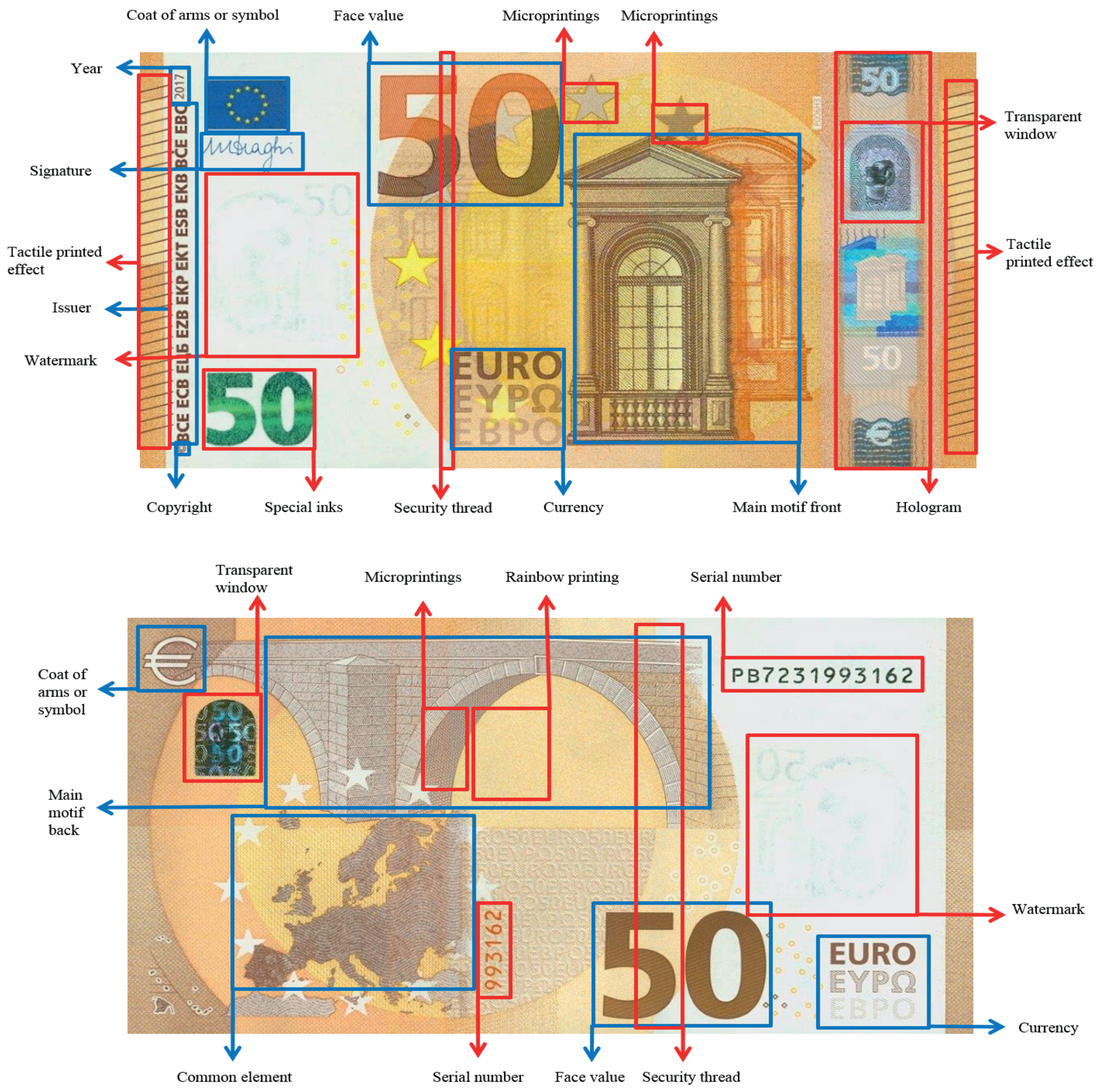
	Country / Manufacturer	Currency	Denomination	Codification
1 Euro banknotes	Eurosystem	Euro	5 (First Series)	EUR 5
	Eurosystem	Euro	5 (Europa Series)	EUR 5 Europa
	Eurosystem	Euro	50 (First Series)	EUR 50
	Eurosystem	Euro	50 (Europa Series)	EUR 50 Europa
	Eurosystem	Euro	200 (First Series)	EUR 200
2 European banknotes prior to euro	Spain	Peseta	1.000	ESP 1000
	The netherlands	Guilder	25	NLG 25
3 International paper banknotes	China	Yuan	20	CNY 20
	Japan	Yen	1,000	JPY 1000
	Switzerland	Swiss franc	20	CHF 20
	Venezuela	Bolivar	5,000	VEF 5000
	Russia	Ruble	100	RUB 100
	South Africa	Rand	10	ZAR 10
	USA	US dollar	100	USD 100
4 International polymer banknotes	Paraguay	Guarani	2,000	PYG 2000
	New Zealand	New Zealand dollar	10	NZD 10
	UK	Pound sterling	5	GBP 5
5 Manufacturer banknote sample	KBA	Koening & bauer	No value	KBA

SOURCE: Banco de España.

with different techniques (offset, intaglio, silkscreen), with distinct face values, colours and main motifs with vertical or horizontal design orientation and security features integration. The reason for such a selection is to present participants with the largest variety of banknote designs and security features possible. For further details, the front and back images of each banknote are depicted in Appendix A.

For all the banknotes, a total of 18 design elements along with 12 security elements have been established to allow further comparison of the eye tracking results. These common areas of interest (AOI) have been duly indicated, both in the front and the back of all the banknotes. Figure 2 shows the case for the EUR 50

Figure 2
EXAMPLE OF A BANKNOTE MARKED WITH AOI ON BOTH SIDES



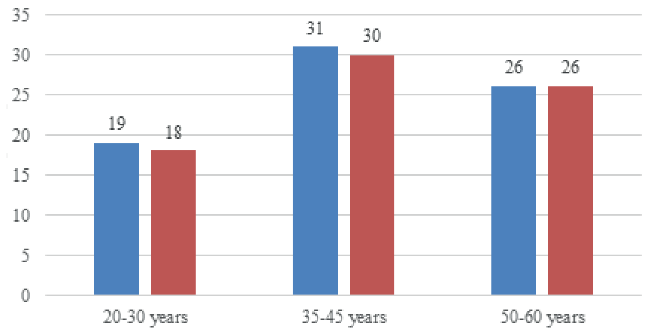
SOURCES: Banco de España and LENI.
NOTE: The areas highlighted in blue correspond to desing and in red to security elements AOI.

Europa series. The complete list of common areas (i.e. design and security elements) is set out in Appendix B.

3.3 Selection of a representative sample of people for testing

The sample of the study consists of 150 people divided into three gender-balanced age groups (20-30, 35-45, 50-60). This segmentation is to achieve a proper age differentiation between

Chart 1
SAMPLE DISTRIBUTION



SOURCES: Banco de España and LENI.

consecutive groups that could lead to appreciable perception differences. Under-age people are not considered in the study owing to legal and ethical aspects. The number of participants in each segment has been defined according to the demographics of the province of Valencia (Spain), where the study is carried out, drawn from the National Institute of Statistics (INE). Based on these percentages the sample was divided as described in Chart 1.

Any person who does not have correct sensory aptitudes (reduced vision, reduced hearing capacity, speech difficulty) will be discarded because, in the event of reduced vision, the eye tracking data could be erroneous and, in the event of reduced hearing and speech difficulty, because the interaction with the interviewer would hinder the test.

Likewise, the sample will be distributed according to the percentage of cash-handling people in order to assess how their knowledge of banknotes affects their perception. The approximate figure is that 65.9% of the province's active population works in the services sector according to the INE. Of course, this sector includes activities that are not related to cash handling (Public Administration, Health, Education, Communications, Culture, etc.). Based on these data, it has been decided that 50% of the population under study should routinely handle cash, which is similar to other scientific studies (Klein *et al.* (2004)).

3.4 Measure of public responses

As the main aim of this study is to validate the potential utility of including neurometric measures in evaluating banknotes, a full set of techniques is employed to extract the entire participant's response, ranging from conscious to human and physiological unconscious response, obtained via questionnaires or with specific sensors, respectively. However, the selection of such techniques can be adapted to the insights of interest along with additional aspects such as the instrument's cost, how easy it is to manage when allowing its use in potential itinerant perception studies, and attempting to secure the least possible interference of the participant.

The techniques used in the study are the following:

Voluntary Response:

— Questionnaires.

Human Behaviour:

— Eye Tracking (ET).

— Facial Expression Analysis (FEA).

— Human Behaviour Tracking (HBT).

Physiological Response:

— ElectroEncephaloGraphy (EEG).

— Measurement of the level of skin conductance, namely through Electro Dermal Activity (EDA).

— Heart Rate Variability (HRV).

3.4.1 Questionnaires

Surveys and questionnaires are explicit responses. They are an excellent tool for capturing respondents' self-reported behaviours and skills, mental or emotional states or personality profiles. However, they are merely momentary snapshots and capture only certain aspects of a person's behaviour, thoughts and emotions.

The questionnaires were carried out at different moments of the study asking the following axes:

— After visualising each banknote (front and back) on the monitor: in this case, there are questions about certain semantic axes such as: aesthetics, quality, design, durability, pleasure, emotional aspects, etc., in addition to an assessment and unconscious association of open attributes for each of the banknotes.

— After visualising all the banknotes: a questionnaire was completed comprising both recall questions (to ascertain which banknotes and security elements were remembered without offering prompts and in which part of the banknote the security elements were located: front, back, top, bottom, left, centre, right)and recognition questions showing images of banknotes, asking the participants whether or not they were shown during the test.

— After interacting with each physical banknote: a questionnaire was completed to assess the material and attributes, similar to the previous phase, but adding attributes related to the feel of the banknote and geometry, texture and relief.

3.4.2 Eye Tracking (ET)

The ET is an implicit response. ET will enable information to be collected on the elements on which the person's attention is focused during banknote evaluation. Then, different types ofmetrics are extracted. One set associated with the entire banknote, such as the number of fixations (fixations are an event denoting a period where the eyes are locked on an object), the mean average duration of these fixations and another set associated with each AOI, such as the visit time or total time fixation for each AOI (total time dedicated to watching that AOI could be presented in time or as a percentage of time spent looking at that AOI compared with the total time the banknote was exposed), the visitors for each AOI (percentage of participants that at least make one fixation on each AOI), those re-visiting (number of participants whose eyes return to an AOI after having made a visual visit to it) or the entry time or time to first fixation (time lapse since new banknote appeared until that AOI was looked at for the first time).

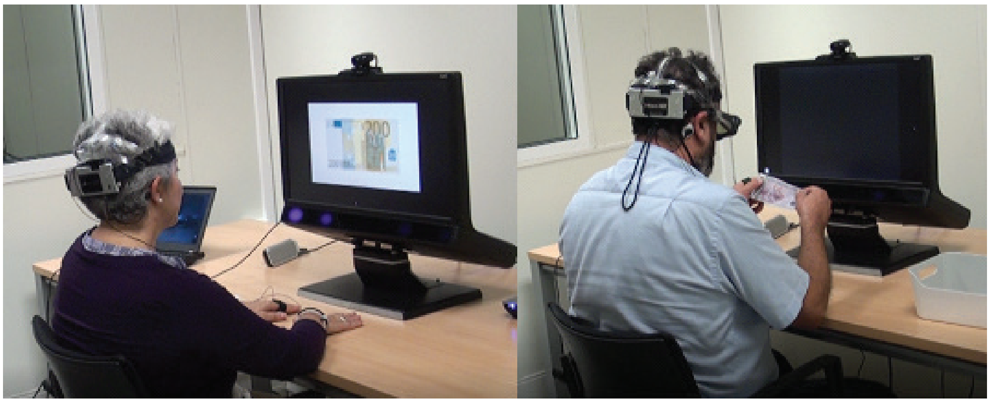
Thank to these metrics, it will be possible to quantify, inter alia:

— The level of interest for each of the banknotes presented.

— Whether the security elements were viewed.

— What other areas were looked at.

— In what order these areas were looked at, which indicates an unconscious order of priority.



Picture 1. Left: Person completing first phase with TOBII TX300. Right: Person completing second phase with SMI glasses.

In this case, the equipment employed was a desktop solution (TOBII TX 300, sample rate of 300 Hz) during the first phase of the evaluation of banknotes on a monitor, and lightweight and comfortable eye tracking glasses (SMI, sample rate of 120 Hz) during the second phase of the evaluation of physical banknotes. Both eye tracking systems can be seen in Picture 1.

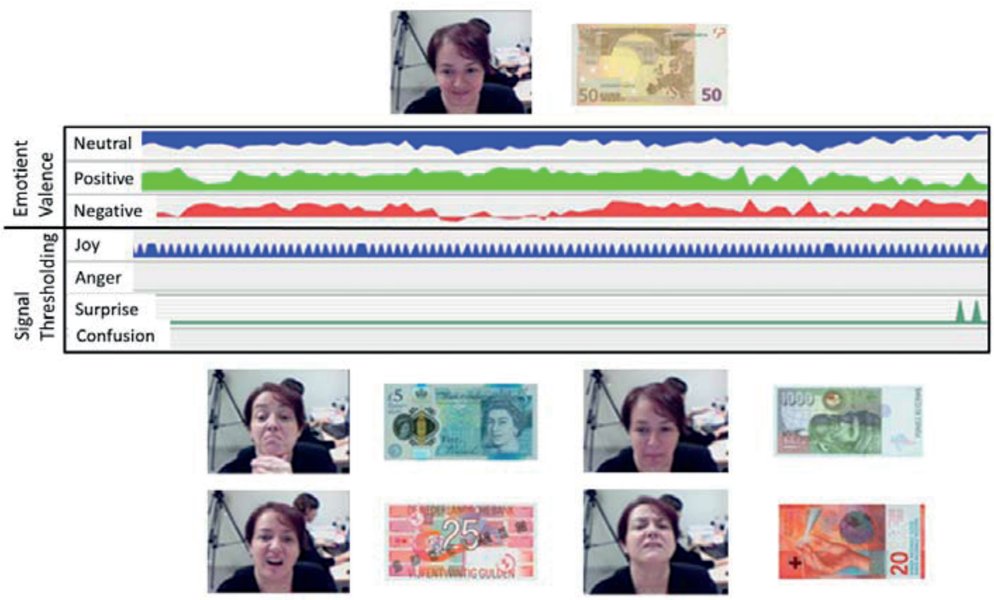
3.4.3 Facial Expression Analysis (FEA)

The FEA is an implicit response. Monitoring of micro facial expressions will allow signs of surprise, confusion, and even level of pleasure, among others, to be extracted. Moreover, as facial expressions are tied to inner emotions, and as emotions rule so much of the behaviour, studying participants' facial expressions gives an insight into the reasons for their actions and whether they are truly expressing their real attitude in observable behaviour.

Facial expression analysis (see Figure 3) is a non-intrusive method that assesses head position and orientation, micro-expressions (such as raising of the eyebrows or opening of the mouth) and global facial expressions of basic emotions (joy, anger, surprise, etc.) using a webcam placed in front of the respondent. Facial data are extremely helpful for validating metrics of engagement, workload or drowsiness.

Figure 3

SOFTWARE FOR GESTURE ANALYSIS OF PARTICIPANTS LOOKING AT THE BANKNOTES



SOURCE: LENI.
NOTE: On the left, the participant gazing at the banknote shown at right.

3.4.4 Human Behaviour Tracking (HBT)

HBT is an implicit response. HBT is another of the innovations of the study to register, by means of the observation of the recorded videos, how the persons handle the banknotes This will provide very interesting information about the way in which the persons inspect the banknotes.

In order to obtain these metrics, a system will be established to allow digital marks to be made during the viewing of the videos of the sessions, thereby enabling the behaviour of the person with the banknote to be coded. The sessions will be double-checked to ensure correct coding. In particular, the following variables will be extracted to include them in the results:

— If the person turns the banknote around.

— If the person folds the banknote.

— If the person looks through the banknote.

— If the person manipulates the banknote to recognise a distinctive sound.

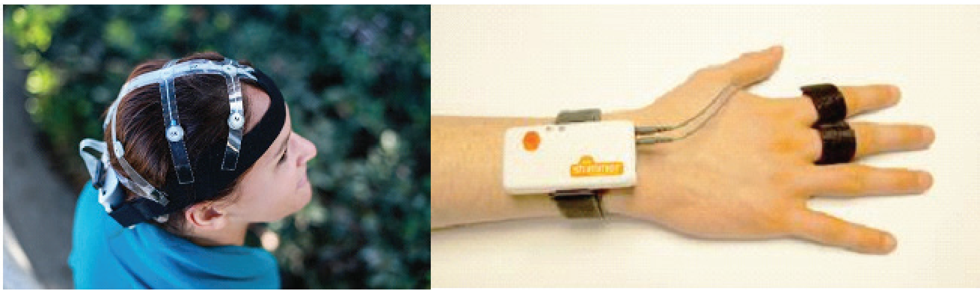
3.4.5 Brain Response. Electroencephalography (EEG)

The EEG is an implicit response. The electroencephalography is a neuroimaging technique measuring the electrical activity generated by the brain from the scalp surface using sensors (electrodes) and amplifier systems. It is ideal for assessing brain activity associated with perception, cognition and emotional processes.

Among all common biosensors, EEG has the highest time resolution, thereby revealing substantial insights into sub-second brain dynamics of engagement, motivation, frustration, cognitive workload and further metrics associated with stimulus processing, action preparation and execution.

EEG impressively provides information about underlying brain processes while it is performing a task or exposed to certain stimuli. Unlike facial expression analysis, EEG is able to monitor the global emotional state of a person, which cannot be controlled consciously – a smile can be faked, but the brain cannot be tricked. The combination of the two modalities provides us with insights into both: the moment-by-moment changes in emotional expression, and variations in emotional states across a longer time span.

For this study, B-Alert EEG wireless equipment (see Picture 2) is used. The B-Alert EEG series from Advanced Brain Monitoring (ABM), for example, offers two cognitive-affective metrics, which have been validated in several academic research projects (Berka *et al.* (2007) and Nussbaum (2012)):



Picture 2. EEG sensor and EDA/HRV sensor employed in the study.

- **Cognitive States** reflect the overall level of engagement, attention and focus during information-gathering and visual scanning. Engagement level is projected to a continuous scale with the extreme poles with values zero (low engagement) and one (high engagement).

- **Workload** reflects any cognitive process involving executive processes such as working memory, problem-solving and analytical reasoning. Workload as associated with theta band activity increases with higher levels of task demands and working memory load, for example when memorising lists or trying to block distracting stimuli in order to focus on task-related elements. Again, the numeric range for workload is from zero to one, with larger values representing increased workload.

Another extended cognitive metric analysed with EEG is Frontal Asymmetry. Considering them together, frontal asymmetries of beta and gamma frequency bands can be interpreted with respect to the amount of motivation towards (approach) or away from (avoidance) a stimulus or mental image (Ohme *et al.* (2010) and Davidson (2004)). Frontal asymmetry can be extracted from EEG headsets with electrodes located at frontal scalp regions, enabling short-term changes in motivation over the course of a stimulus presentation to be analysed.

3.4.6 Electro dermal activity (EDA)

EDA is an implicit response. EDA, also referred to as galvanic skin response (GSR), reflects the amount of sweat secretion from sweat glands in our skin. Increased sweating results in higher skin conductivity. When exposed to emotional stimulation, we “sweat emotionally”, particularly on our forehead, hands and feet. Like pupil dilation, skin conductance is controlled subconsciously, therefore offering tremendous insights into the unfiltered, unbiased emotional arousal of a person.

EDA measurements can be made with lightweight and mobile sensors, which makes data acquisition very easy. Additionally, automatic data analysis procedures extract key metrics on the fly, giving immediate access to the underlying changes in emotional arousal (Vecchiato *et al.* (2010)). By means of a bracelet sensor the level of stress / relaxation and emotional excitation of the person in the face of the task proposed in each case can be quantified. In this case, the Shimmer GSR sensor that can be seen in the Picture 2 has been used.

3.4.7 Heart Rate Variability (HRV)

HRV is an implicit response. To analyse HRV, the electrocardiogram (ECG) signal needs to be filtered (Blanco-Velasco *et al.* (2008)), studied to detect QRS zones (Pan *et al.* (1985)) and revised manually by an expert, because the appearance of a single ectopic can produce variations in certain key parameters extracted from this analysis (Clifford *et al.* (2006)). HRV analysis can generate a set of metrics that can be extracted from different dimensions like time and frequency domains.

HRV is based on tracking heart rate, or pulse, from ECG electrodes or optical sensors (see Picture 2) to gain insights into respondents' physical state, anxiety and stress levels (arousal), and how changes in physiological state relate to their actions and decisions.

3.5 Application of the neurometric methodology to banknotes and security features design

3.5.1 Participant groups

The sample of 150 participants is divided into two groups: the ADVANCE group and the NEUROADVANCE group, in which two sets of measurement instruments will be tested. It was divided into two groups to test two possible evaluation configurations. The ADVANCE group includes measures of behaviour analysis such as eye tracking, facial expression analysis and human behaviour tracking that do not require any sensor to be placed on the body of the person but are mainly based on optical systems that analyse where the participants look and what gestures they make. This type of configuration is easier to implement and replicate in hundreds of measurement points, with a low measurement complexity and cost. In the NEUROADVANCE group, we would keep the advance group's sensors (which will therefore be in the whole sample), but with several additional physiological measures which would allow us to collect the brain response, cardiac variability and skin conductance. These sensors are more invasive and complex to apply and to analyse the signals. Nevertheless, they provide implicit information of great interest for the banknote perception valuation. To analyse the contribution of each configuration, the two measuring configurations will follow an identical protocol.

3.5.2 Advance group

This group comprises 100 persons examined with low-cost and easy implementation instruments to let the study replicate in itinerant points. As this set of selected measures is the most viable for adoption in recurrent studies, this group comprises the majority of the sample. The measurements obtained are:

— Eye Tracking (ET).

— Facial Expression Analysis (FEA).

— Human Behaviour Tracking (HBT).

— Answers to questionnaire.

3.5.3 Neuroadvance group

This group comprises 50 persons which include the signals of the previous group plus physiological signals that involve placing certain sensors on the participant's body. Thus, in addition to the advance group's measurement set, which is also included in this group, the following measures are also obtained:

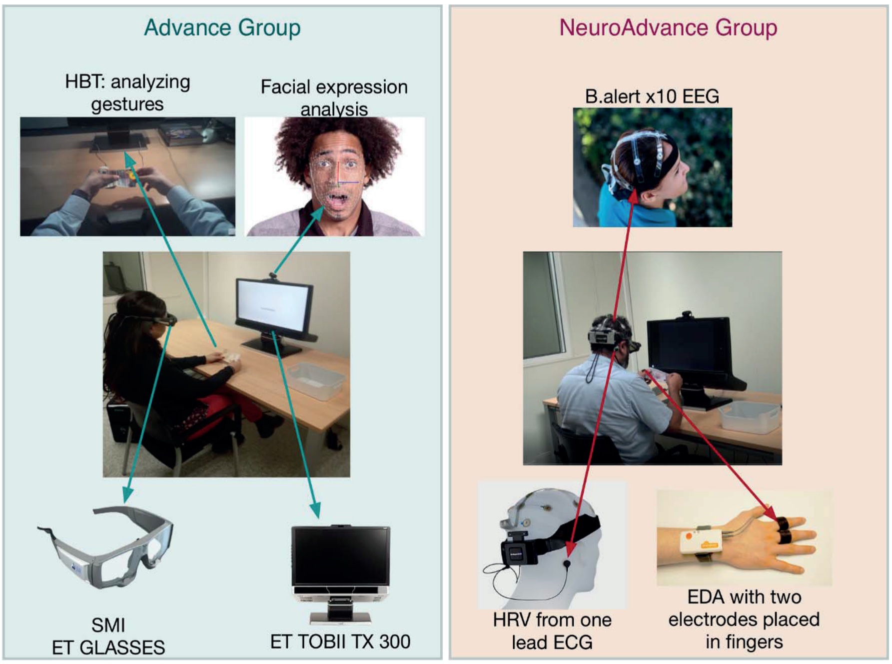
— Electroencephalography (EEG).

— Electro dermal activity (EDA).

— Heart rate variability (HRV).

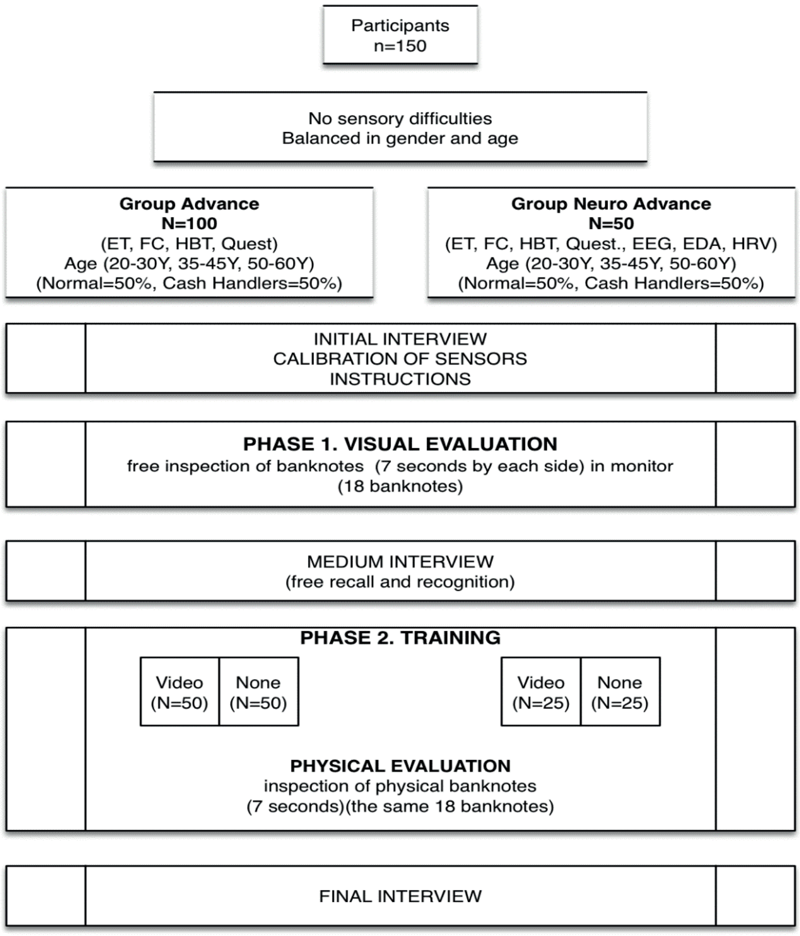
The set-up of the two groups is detailed in Figure 4.

Figure 4
SET-UP OF THE TWO GROUPS



SOURCE: LENI.

Figure 5
DESIGN PROTOCOL OF A NEUROMETRIC STUDY



SOURCES: Banco de España and LENI.

With this configuration, invasiveness, test time, complexity in measurement and the possible cost are increased, but there are gains in sensitivity when carrying out the implicit, cognitive and emotional measurement of the person.

Figure 5 depicts the design protocol of a neurometric study.

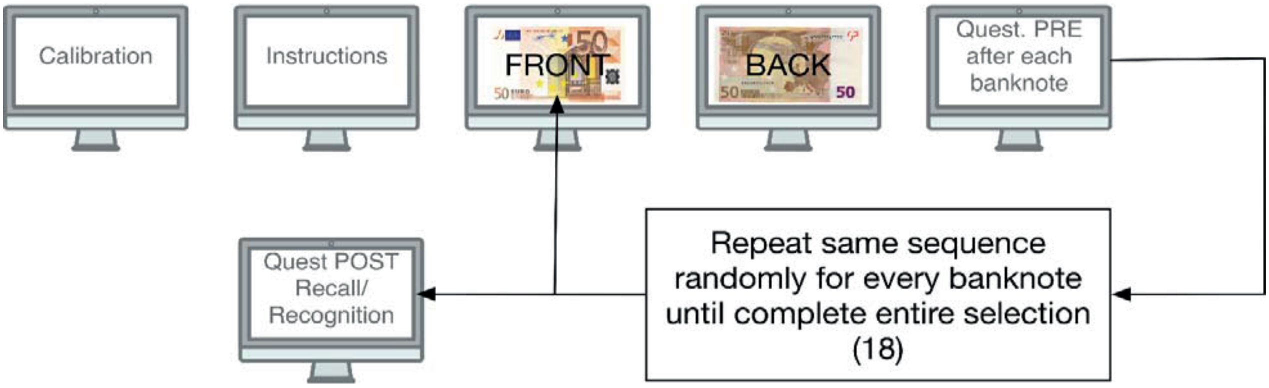
3.6 Evaluation phases

Both advance and neuroadvance groups complete the same methodology, which consists of two main evaluation phases (visual and physical) and a training phase.

3.6.1 Visual evaluation - First phase

Following an initial calibration, the person visualises the instructions on a monitor and then evaluates each banknote presented on both sides. Each side is viewed for 7 seconds.

Figure 6
DESIGN OF PHASE 1: VISUAL EVALUATION



SOURCES: Banco de España and LENI.

Once each banknote is displayed on both sides, the participant completes a questionnaire called "PRE" which values certain semantic axes and the association of open attributes. This mechanism is repeated for all the banknotes randomly presented.

Once the participant finishes viewing and evaluating all the banknotes, the participant answers a "POST" questionnaire with recall and recognition questions.

3.6.2 Physical evaluation and training - Second phase

In this second phase, each ADVANCE and NEUROADVANCE group is divided in half. Only one of the two halves of each group watches a training video on banknote security features, in order to compare to what extent the training influences banknote perception.

Picture 3. Person completing phase 2 with a physical evaluation of samples.

The video, approximately three minutes long, shows how to detect some security features that usually appear on banknotes via the so-called “feel, look and tilt” method.

Moreover, in this phase, all the participants, trained or not, handle and evaluate each banknote for 7 seconds. Particular attention is paid to how they manipulate the banknote, i.e. whether they turn the banknotes, the number of turns, what they touch, whether they see through the banknotes, etc. In this way, we take into account the senses of sight and touch. After handling each banknote, a pre-questionnaire similar to that of the previous phase but adding attributes of the substrate and the banknote touch sensation – such as its texture and raised print – will be completed by each participant. This process is repeated with all the banknotes, randomly presented. Additionally, the test is recorded by an external camera. As in the first phase, after receiving each banknote, the persons validated certain aspects relating more, in this case, to the physical attributes of the banknote.

4 Data analysis and statistical methods[1]

In order to test comparisons of means of the calculated metrics, a set of Kolmogorov-Smirnov tests were conducted to assess whether dependent variables deviated from normality. Then a statistical analysis was performed using ANOVA to compare between groups of population and a repeated measures test was carried out to compare the impact that different banknotes had on participants. A corrected p-value less than $p<.05$ was chosen to correct multiple comparisons effect (Feise (2002)). To obtain the correlation between neurometrics, a Pearson correlation was applied.

4.1 Neurometrics related to the visual interest of the design

Banknote Visual Interest Score (BVIS)

This is a metric related to the interest at visual level that the design of the banknote or communication material arouses. This high level metric focuses on a non-linear model that establishes a score of the interest at a visual level that the design of the banknotes or security feature or communication materials generates and that allows comparison between different types of designs. For its calculation, several biometric variables are considered which contain information regarding the eye tracking signal, such as:

— The viewing time of the areas of interest related to the design of the banknote or communication material vs. the viewing time of the security zones of the banknote or other areas of interest of the communication materials.

— The total time allocated to the visualisation of the banknote or communication material in comparison to the visual navigation outside the banknote or communication material.

— The visualisation sequence of the design elements of the banknote or communication material vs. the security features of the banknote or other areas of interest of the communication materials.

— The ratio of quadrants per second of the banknote or communication material that navigates the user's eye dividing the banknote or communication material into 8 quadrants.

— The percentage of banknote or communication material scanned.

— The ratio between the numbers of broad movements vs. short movements of the eye within the banknote or communication material (ambient to focus).

1 The Kolmogorov-Smirnov test (also test K-S) is a non-parametric test that determines the goodness of fit of the probability distributions with each other. An analysis of variance (ANOVA) tests the hypothesis that the means of two or more populations are equal. The Pearson correlation coefficient is a measure of the linear relationship between two quantitative random variables, irrespective of the scale of measurement of the variables.

Within this metric a characteristic graphic can be obtained, namely the Banknote Behavioural Map (BBM). This graphic represents how the visual perception has been made on both sides of the banknote or communication material; the sequence in which the gaze has travelled through the different areas of interest; whether the eye revisited any of the areas of interest; and what percentage of the sample visited at least once each of the areas of interest.

4.2 Neurometrics related to the activation of cognitive functions

Banknote Engagement Index (BEI)

This metric refers to the level of sustained functional attention that the person is applying to the perception of the banknote or communication material. This indicator is very interesting because it reflects whether the banknote or communication material is of interest to focus on it and also because it helps discern whether the person is focused on the task and, therefore, whether the rest of the metrics obtained in that moment are of value. To calculate BEI, regard was had to the processing of the physiological response (analysis of the brain signal) and the analysis of the behavioural signal (ocular tracking of the person).

Banknote Workload Index (BWI)

This metric refers to the cognitive load or mental effort that the process of perception and valuation of certain attributes of the banknote or communication material involves for the person. It is very important since a high cognitive load can mean that there is a saturation

Chart 2
BANKNOTE COGNITIVE MAP (BCM)

SOURCES: Banco de España and LENI.

of information which leads to rejection, but at the same time a low value can indicate boredom which is also negative. To calculate BWI, regard wad had to the processing of the physiological response (analysis of the brain signal) and the analysis of the behavioural signal (ocular tracking of the person).

There is a type of graph where the two indicators are related by positioning each banknote, security feature or educational and training material evaluated on a map where an optimal zone is established. This allows different designs at the cognitive level to be intuitively compared. It is what it is called the Banknote Cognitive Map (BCM).

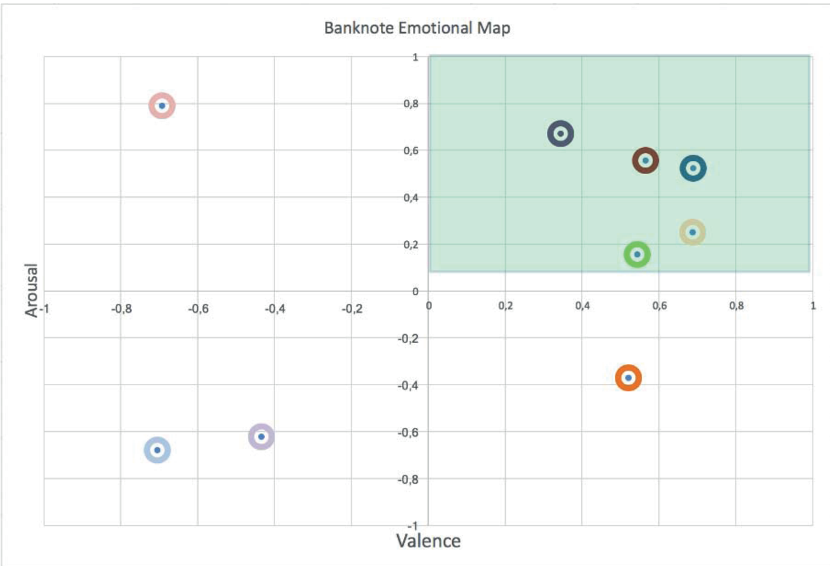
4.3 Neurometrics related to the capacity of emotional induction of the banknote

Banknote Emotional Induction Index (BEII)

This metric is based on calculating the ability to induce certain emotional states in the person. The BEII is based on the calculation and representation of a point on a two-dimensional spatial axis in which the emotional excitation capacity (Arousal) and the ability to generate a positive or negative emotion (Valence) are extracted. To calculate these two dimensions that support the BEII, signal processing from behavioural measurements (micro facial expressions during banknote viewing) and the physiological response (cerebral hemisphere asymmetry, cardiac variability and conductance skin) are used.

Chart 3 shows the Banknote Emotional Map (BEM).

Chart 3
BANKNOTE EMOTIONAL MAP (BEM)



SOURCES: Banco de España and LENI.

4.4 Neurometrics relating to banknote security technology

Banknote Security Capacity Index (BSCI)

This indicator reflects the capacity of the security elements and banknote design for being authenticated by the public. This indicator is based on several parameters related to the behavioural signal (e.g. eye tracking of the security elements of the banknote, automatic tracking of the participant's interaction gestures with the banknote) and voluntary response values of the participants. Through the modelling of these parameters, an absolute index can be obtained that allows for the comparison of new security elements and designs in a single banknote or the comparison of current security features and designs of different banknotes.

4.5 Banknote Neurometric Final Score

The calculation of a global score that provides a snapshot of the banknote's performance or communication material is established through the previous calculation of the indicators, which allows a quick assessment and comparison with other banknotes or communication materials that have been evaluated.

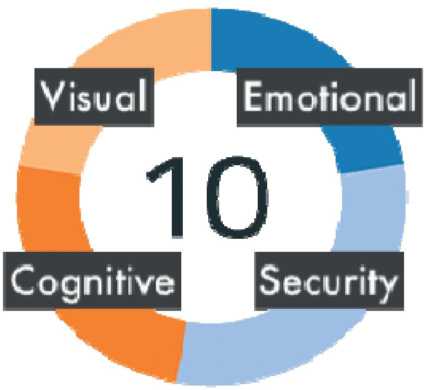
The score will be from 1 to 10 through a mathematical equation comprising four indicators, which include five neurometrics. These will influence one another with configurable weights.

These indicators are:

Visual:

— Banknote Visual Interest Score (BVIS).

Figure 7
BANKNOTE NEUROMETRIC FINAL SCORE



SOURCES: Banco de España y LENI.

Cognitive:

— Banknote Engagement Index (BEI).

— Banknote Workload Index (BWI).

Emotional:

— Banknote Emotional Induction Index (BEII).

Security:

— Banknote Security Capacity Index (BSCI).

The integration of the four indicators, containing the five neurometrics, in order to obtain the Banknote Neurometric Final Score is shown in Figure 7.

5 Main Findings

Presented here are some of the results drawn from the analysis of the data collected from the participants as an introduction to the potentiality of neurometrical science for banknotes.

5.1 Findings in the visual evaluation – First phase

5.1.1 Eye tracking: Areas of interest

Chart 4 shows the visit time percentage of the design AOIs presented on, at least, half of the banknotes. In order to calculate the percentages, firstly the time during which one person visited an AOI is calculated as a percentage of the total available time for this side of the banknote. Finally, the mean of the dwell time of all participants and banknotes that contain this AOI is calculated.

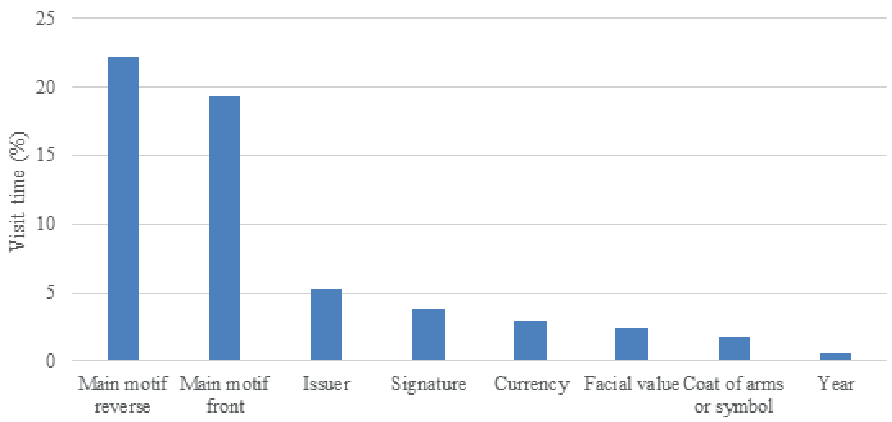
The main findings that can be highlighted are:

— Both the front and reverse main motifs clearly show significant statistical differences (average around 23% of time, $p<.05$) from the rest.

— A big dispersion can be noticed on these two AOIs, indicating that these values vary among different banknotes and participants.

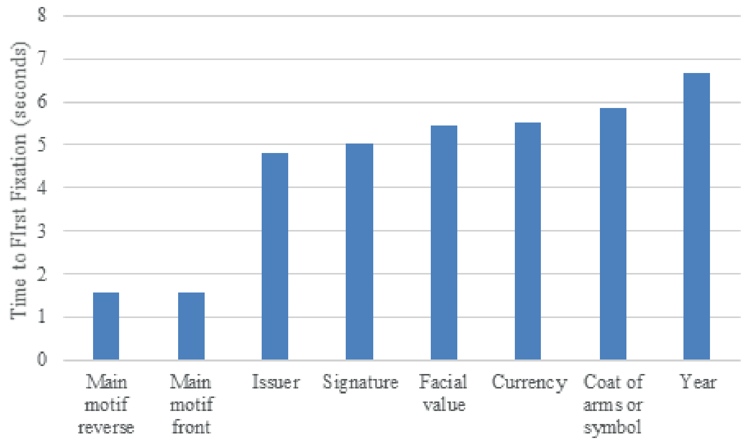
— In the group of least visited AOIs, the currency and face value curiously perform worse than the issuer and signature, although the former occupy in most of the banknotes a bigger space than the latter.

Chart 4
AVERAGE OF VISIT TIME FOR EACH DESIGN AOI IN ALL BANKNOTES IN PHASE 1



SOURCES: Banco de España and LENI.

Chart 5
AVERAGE OF TIME TO FIRST FIXATION OF EACH DESIGN AOI IN ALL BANKNOTES IN PHASE 1



SOURCES: Banco de España and LENI.

Chart 5 shows the time to first fixation (TTFF) of the design AOIs. Therefore, the TTFF is the lapse time between the appearance of the banknote and the first fixation to each AOI, with the TTFF assigning the total banknote exposure time should a participant not look at that AOI. Finally, the mean of the TTFF for all persons and banknotes that contain this AOI is calculated.

The main findings to be underlined are:

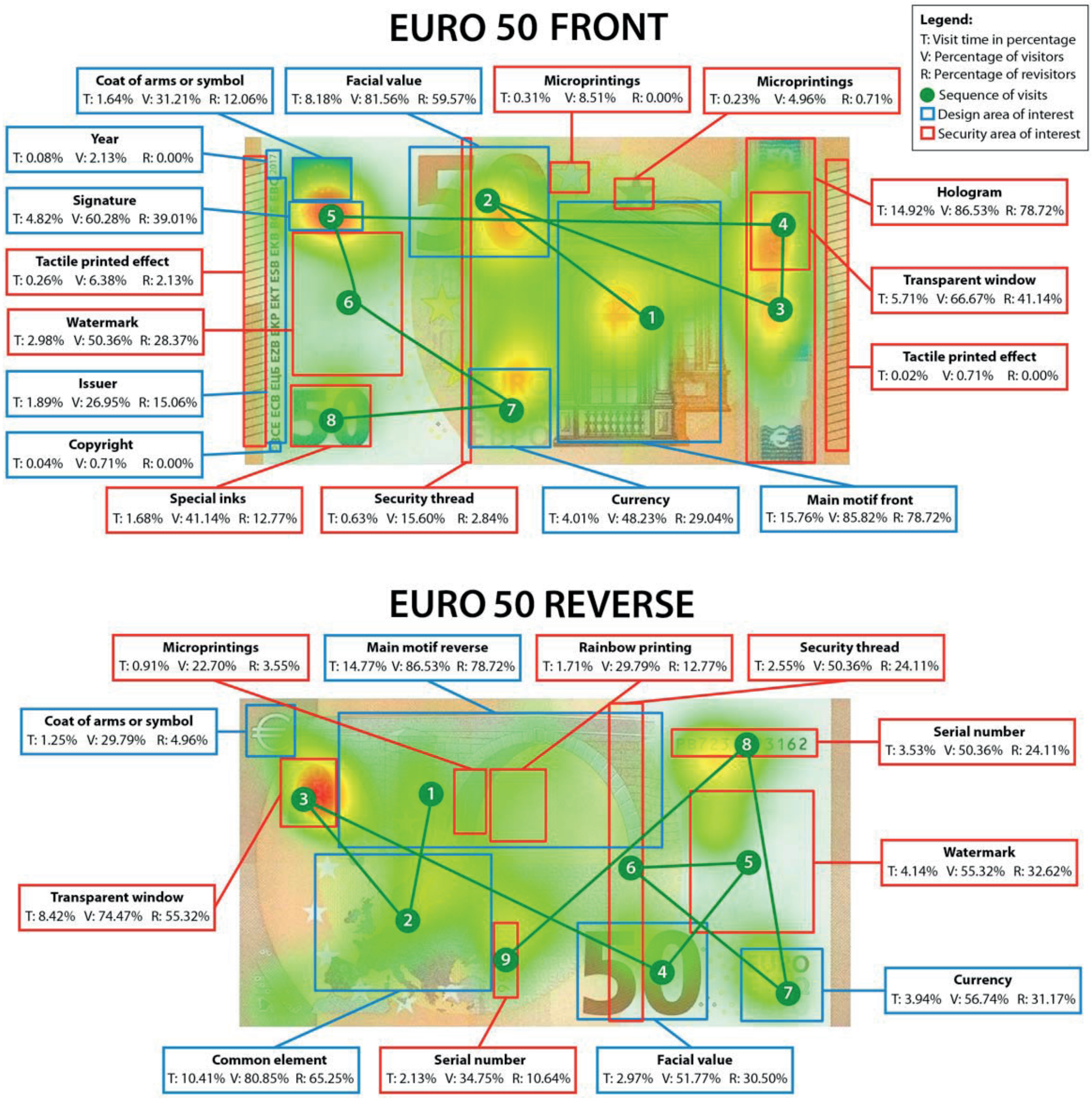
— Not only the main motifs were the most viewed, as we have seen before, but they were also those, initially, at which the eye was directed (at the first second of exposition of the banknote), showing a significantly higher visual interest compared to others ($p<.05$).

— Despite being smaller in size, the issuer and the signature were looked at before (average around 5 seconds) the currency and the face value (significant differences, $p<.05$, between the issuer and the signature with respect to the currency, the coat of arms and the year).

5.1.2 Eye tracking: Banknote Behavioural Map (BBM)

Thanks to the precision of eye tracking, a visual attention level analysis of each AOI for all the banknotes can be performed. Figure 8 shows the banknote behavioural map (BBM) of the EUR 50 Europa series, as a sample of the potential of this analysis. The BBM includes: (1) the image of the banknote, (2) the heat map of fixations on the banknote, (3) the segmentation of AOIs divided into design (blue) and security (red), (4) the visit time

Figure 8
BANKNOTE BEHAVIOURAL MAP (BBM) OF THE EUR 50 EUROPA SERIES IN PHASE 1



SOURCES: Banco de España and LENI.

(T) of the AOI as a percentage of total available time for this side of the banknote, (5) the percentage of visitors (V) who look at the AOI at least once, (6) the percentage of revisitors (R) that look at the AOI at least twice, and (7) the sequence (numbered green line) of visits using the average time to first fixation (TTFF).

The BBM main findings for the analysis of the EUR 50 Europa banknote are:

— The front and reverse motifs and the hologram are the most visited and revisited areas of the banknote.

— The order of watching always start on the main motif, both in front and reverse.

— The common element has a good rate of visits (80%) and it is the second AOI being watched for the first time.

— The transparent window receives later attention in the sequence of gaze, and the participants do not spend too much time watching it.

— The currency is the last design AOI watched.

— The difference between security and design feature highlights, the latter being considerably predominant.

5.1.3 Brain response: engagement, workload and asymmetry

Regarding the EEG signal, Chart 6 presents the average of engagement, workload and the percentage of the time during which the asymmetry was positive for each banknote. In all cases, the mean of both sides of the banknotes is calculated.

Regarding engagement, it is associated with the participants' attention to collect information while visually scanning the banknotes. The results show that the banknote design with the greatest engagement is the GBP 5, followed by the CNY 20 and the JPY 1000 banknotes.

However, this does not happen either with the CHF 20 or with the USD 100 that have been identified as a store of value at the verbalisation, simply by virtue of the banknote's country of origin. It is their design that prevents them from generating engagement. In the case of CHF 20, this is because its design is too complicated; and in that of USD 100, because it is too traditional.

The case of RUB 100 does not generate a significant engagement. The participant finds it difficult to achieve a medium level of engagement with design elements, such as the athlete snowboarding, and they less confidence than others.

On the other hand, it may be affirmed that banknotes from well-known currencies, like the GBP or the JPY, generate engagement. Also, banknote designs that include images of women and/or animals and are monochromatic (ZAR 10, PYG 2000, NZD 10, VEF 5000)generate an acceptable level of engagement because these are novel elements for the population of study which attract and engage them, regardless of the country of origin of the banknote. This group may include the design of the KBA banknote, which is also monochromatic and presents less common banknote images, such as a main motif with two persons.

In the case of euro, the engagement results are lower than expected. This might be because of the familiarity of the sample with the banknotes and, consequently, the level of attention and visual interest decline compared to more unknown banknotes.

Chart 6
AVERAGE OF ENGAGEMENT, WORKLOAD AND ASYMMETRY OF EACH BANKNOTE

SOURCES: Banco de España and LENI.

Workload is associated with the demands and efforts needed to execute a task. Hence, in this study, it is an index that indicates the mental effort made during the visualisation of the banknote. From the results, it can be stated that the banknotes that need more mental effort are the CHF 20, the EUR 50 Europa, the ZAR 10, the PYG 2000 and the KBA and the CNY 20, owing to several reasons. The mental effort in the CHF 20 may be due to the number of elements that are mixed in its design, the striking colours and the need to find a meaning to the symbolism of the hand with the prism that appears as the main motif. On the other hand, the EUR 50 Europa generated a higher workload than expected because it was issued recently and the participants made a greater mental effort as the banknote was not so familiar to them. In ZAR 10 and PYG 2000 banknotes, which differ from a traditional design which the participants are used to, the mental load is due to the need to decipher each of the elements that appears on the design of these banknotes in addition to the possible confusion that the PYG 2000 generates, as it does not keep a heterogeneous design style, representing disparate scenes on both sides of the banknote. The same applies to the CNY 20 banknote. In the KBA banknote the mental effort may be due to the confusion that it generates since it was difficult to identify it as a banknote, i.e. neither the value nor the country appears on the sample.

The banknotes with the lowest workload are the EUR 5 and the NLG 25. The reason for the EUR 5 can be associated with its familiar and simple design. And, in the case of the NLG 25, owing to its simple and consistent design.

It could be said that the banknotes that present a design in which front and back do not show the same aesthetic line and where the elements represent the same scene need a greater cognitive effort when visualising them. On the other hand, banknotes that have a simple design do not generate workload. Hence, this metric is very useful for designing banknotes with a level of complexity so as to generate a correct cognitive load, associated with interest, but not in excess since it could saturate the user and cause rejection.

Asymmetry is associated with emotional and motivational processing during the observation of stimuli. A higher asymmetry reflects a greater approach to the visual stimulus presented. From Chart 6, it can be inferred that the participants have a tendency to identify themselves in banknotes such as the EUR 50 Europa, NLG 25, CHF 20, ESP 1000, JPY 1000, GBP 5, VEF 5000, ZAR 10 and USD 100. We think that the element that generates this identification is the confidence given by the country of origin of the currency.

However, RUB 100, CNY 20 and some euro designs do not generate identification. In the case of RUB 100, this may be due to the fact that it portrays images that people do not accept as appropriate for illustrating a banknote. Yet in the case of the CNY 20, the rejection may be because of to the connotations of the front main motif of the banknote, as it generates controversy. In the case of euro, it may be due to the fact that the participants do not associate the main motifs with any actual known monument.

It is possible to affirm that the designs that generate confidence because of the banknote's country present greater identification with the banknote, while ignorance of the decorative elements of design and the connotations that generate controversy cause loss of identification towards the design of those banknotes.

Table 3 summarises the ANOVA results, taking into account the possible differences in the brain's response considering factors such as gender or age of the participants or whether they were people who usually handle money or not, and, in the event of significant differences, which group presents a higher value. This Table 3 only shows the groups where significant differences have been found.

Table 3
ANOVA RESULTS FOR EEG MEASUREMENTS

Metrics EEG	Gender	Age	Cash handler
Mean engagement	(M > F)	(50-60 > 20-30)	(NCH > CH)
Mean workload		(20-30 > 50-60) (35-45 > 50-60)	
Mean asymmetry		(30-40 > 20-30) (50-60 > 20-30)	

SOURCES: Banco de España and LENI.
NOTE: Significant differences (p<.05) between gender (M: male, F: female), age (20-30 years, 35-45 years, 50-60 years) and cash handlers (CH: cash handler, NCH: non-cash handler) in EEG.

From Table 3, it can be inferred that:

— There are significant differences in gender in the engagement with higher values in the male group.

— There are significant differences in age in the engagement with higher values in the 50-60 years' group vs. 20-30 years' group, who are less familiarised with banknotes and in workload with higher values in 20-30 years vs. 50-60 years and higher values in 35-45 years than 50-60 years. It seems that is easier for older people to understand and evaluate banknotes. In asymmetry, results show that young people are least close to the banknotes.

— There are significant differences in cash handlers (CH) vs. non-cash handlers (NCH) in the engagement with higher values in the non-cash handlers group vs. the cash handlers group that are familiarised with banknotes.

— The age seems the most relevant factor of the three that influence cognitive responses.

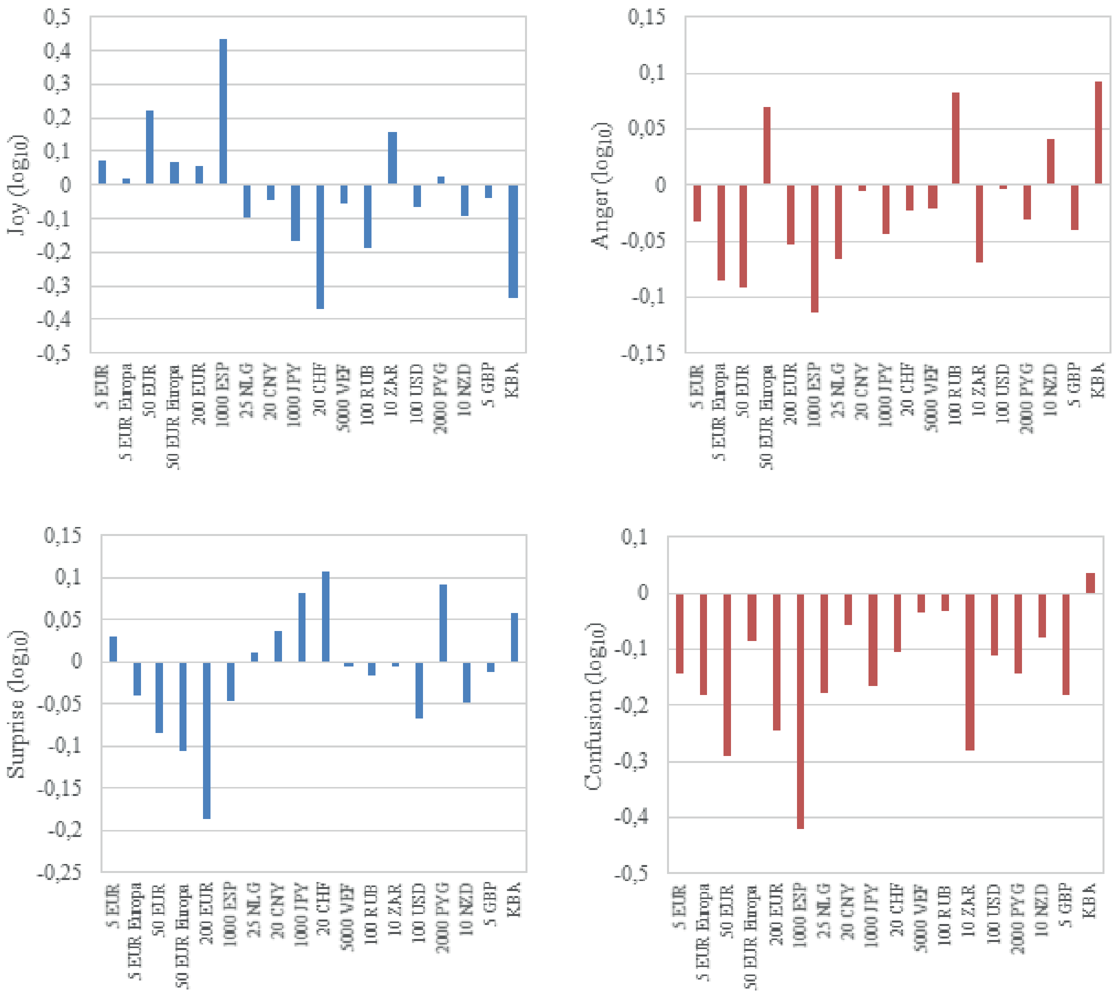
5.1.4 Facial Expression Analysis: emotions

Regarding Facial Recognition, Chart 7 shows the four selected emotions that are more likely present at the moment of the banknote perception, where the evidence of a target expression to be present is represented in logarithmic scale. An evidence value of 0 means that there is an equal chance that the expression could be categorised by an expert human coder as joyful as opposed to not joyful. An evidence value of 1 in the joy channel means that the observed expression is 10 times more likely to be categorised as joyful as opposed to not joyful by an expert human coder.

The main findings regarding emotions drawn from facial expressions are that the banknote that generates most happiness is the ESP 1000, probably because people recognise it well and it evokes nostalgia. Moreover, the green colour is identified as

Chart 7

AVERAGE OF JOY, ANGER, SURPRISE AND CONFUSION FOR EACH BANKNOTE



SOURCES: Banco de España and LENI.

cheerful and suitable for the banknote. The ZAR 10 banknote generates joy both for its green colour and its front image of Mandela. Likewise, the PYG 2000 banknote generates happiness on account of the colour used, which conveys this feeling even though it is not considered as a usual colour on the banknote.

While all euros generate happiness, it is the EUR 50 that generates most, which may be due to its value, familiarity and habit of use.

On the other hand, the banknote that generates least happiness is the CHF 20; despite it having bright colours, they are perhaps too singular. Furthermore, the mixture of different elements in which the person does not find consistency generates confusion that makes it impossible to generate joy. The KBA banknote does not generate joy because the participant just does not understand it nor identify it as a banknote.

The banknotes that generate anger or irritation include the following: the KBA banknote, the RUB 100, the EUR 50 Europa and the NZD 10. For the interpretation of these results, verbalisation and questionnaire results (see Appendix C) have been correlated. The KBA banknote could generate confusion because there is no face value on it, which makes it impossible to identify its value and the country of origin. For RUB 100, the participants were not able to identify it, especially because sports motifs are not associated with a regular banknote, and this fact can generate some surprise. On the other hand, when the EUR 50 is viewed in both series, i.e. first and Europa, the participant may show signs of annoyance since he considered that the banknote had been previously visualised and they were afraid of making a mistake. The NZD 10 generates irritation or anger even though its assessment has been positive in the design elements. But it should be noted that it is not considered to be a traditional banknote and the illustrated images are not deemed appropriate for a banknote even though they are attractive and capture attention.

With regard to the feeling of surprise, the banknotes that generate a bigger surprise are the CHF 20 followed by the PYG 2000, the JPY 1000, the KBA, the CNY 20 and the NLG 25. The EUR 5 banknote generates surprise because of the fact that two banknotes with equal face value but different design have been displayed. In the case of banknotes such as the CHF 20, the KBA banknote and the NLG 25, the surprise generated can be influenced by the fact of their not being considered as traditional, but innovative, banknotes, and their not being identified as such. The PYG 2000 surprises because both sides do not have a common design and, especially, the reverse, rated with high political connotations, has design elements not considered traditional. On the other hand, JPY 1000 and CNY 20 generate surprise which may be caused because they do not present a consistent design on both faces.

Regarding confusion, the only banknote that generates confusion is KBA, since neither the country nor the face value are identified as these elements do not appear on the banknote. In this respect, it seems essential to clearly identify both the value and the origin of the banknote when it comes to avoiding confusion.

Table 4 shows the ANOVA results, taking into account the possible differences in the facial gesture considering factors such as gender or age of the participants or whether they were people who usually handle money or not, and, in the event of significant differences, which group presents a higher value. This Figure only shows the groups where significant differences have been found.

From Table 4, the following conclusions can be deduced:

— There are significant differences in all selected emotions.

— The emotionality in all the axes is significantly higher in people who do not handle money compared to the people who usually handle money.

Table 4

ANOVA RESULTS IN FACIAL GESTURES EMOTIONS DETECTED

Metrics	Gender	Age	Cash handler
Joy		(20-30 > 35-45) (20-30 > 50-60)	(NCH > CH)
Anger	(F > M)	(35-45 > 20-30) (35-45 > 50-60)	(NCH >CH)
Surprise	(M > F)	(20-30 > 35-45) (35-45 > 50-60) (20-30 > 50-60)	(NCH > CH)
Confusion	(M > F)	(20-30 > 50-60) (35-45 > 50-60)	(NCH > CH)

SOURCES: Banco de España and LENI.
NOTE: Significant differences (p<.05) between gender (M: male, F: female), age (20-30 years, 35-45 years, 50-60 years) and cash handlers (CH: cash handler, NCH: non-cash handler) in Facial Gesture Emotions detected.

— Women show anger to a greater extent, whereas in surprise and confusion it is men who show the most significant response.

— In terms of age, young people aged 20-30 show greater joyfulness, while in the case of anger, adults aged 35-45 manifest greater responses. In the case of surprise, this emotion reduces with age. And in the case of confusion, the over-50s group shows the least level of confusion.

5.1.5 Correlations between explicit measures vs. implicit measures

In order to compare the knowledge obtained by the implicit (neurometrics) and explicit (questionnaires) metrics, we analyse the correlations between the Questionnaire and EEG/Facial Expression Analysis responses.

On the one hand, there are 66 possible correlations between the 22 variables of the questionnaire and the 3 of EEG. 33% of these correlations (22 cases) evidence significant differences, and all of them present a weak correlation based on Pearson's coefficient. The higher value achieved for the Pearson's correlation (r=.16) is between brain asymmetry and futuristic evaluation.

On the other hand, there are 264 possible correlations between the 22 variables of the questionnaire and the 12 of Facial Expression Analysis. 43% of these correlations (114 cases) present significant differences, and all of them likewise show a weak correlation. The three most relevant correlations are between joy and confidence (r =.10), confusion and identifiable (r = -.09) and joy and identifiable (r=.08).

5.2 Findings in the Physical evaluation and training - Second phase

In this phase, the banknotes were physically presented to the person so that the participant could assess especially the security elements and physical properties of the banknote.

5.2.1 Eye tracking: Areas of interest

Chart 8 shows the percentage of visit time of the security AOIs during phase 2. In order to calculate the percentages, the time that one person has visited an AOI as a percentage of total available time for this side of the banknote is first calculated. Finally, the mean of the visit time of all persons and banknotes that contain this AOI is calculated. In this section, only the AOIs that are present on half of the banknotes at least are considered.

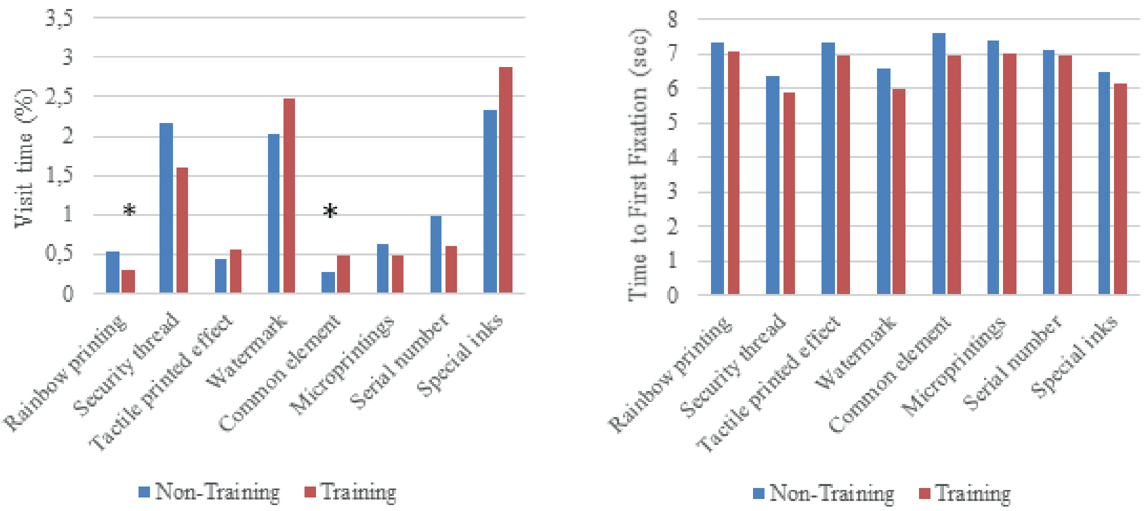
The main findings that we can review in this case are:

— In general, the most viewed elements have been the special inks, the watermark and the security thread.

— In the training group relative to the non-training group, more attention was paid to special inks, the watermark, the tactile printed effect and the common element (p <.05).

— In the non-training group, meanwhile, more attention was paid to the thread.

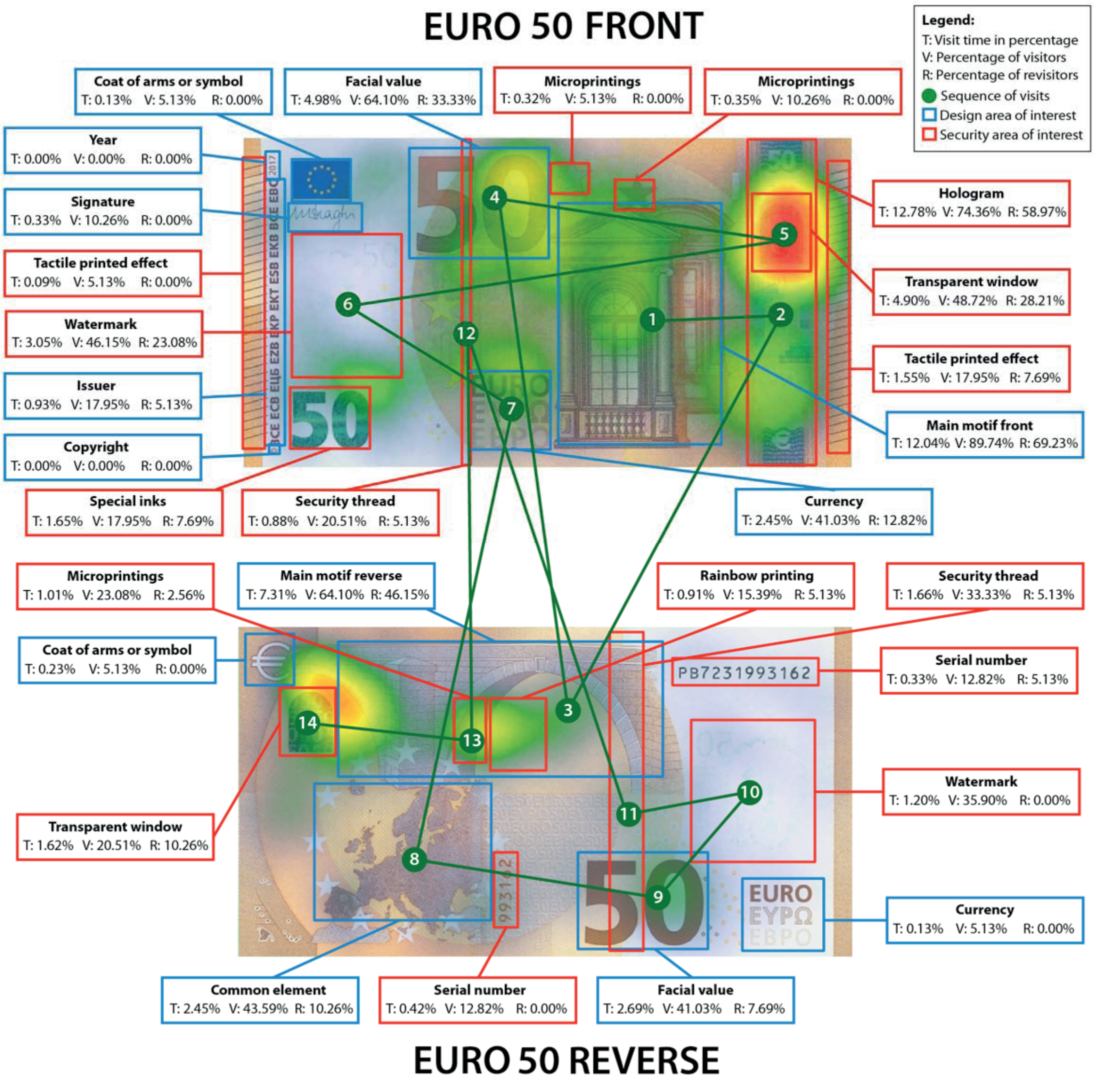
Chart 8
AVERAGE OF VISIT TIME AND FIRST FIXATION IN PHASE 2



SOURCES: Banco de España and LENI.
NOTE: Visit time and Time to First Fixation during phase 2 comparing people that received training and people that did not receive training. Asterisk (*) in comparisons with significant differences (p<.05)

Figure 9

BANKNOTE BEHAVIOURAL MAP OF THE BANKNOTE OF EUR 50 EUROPA SERIES IN PHASE 2



SOURCES: Banco de España and LENI.

5.2.2 Eye tracking: Banknote Behavioural Map (BBM) in phase 2

Figure 9 pictures a BBM of the EUR 50 Europa series banknote during phase 2 of the study.

Analysing the data obtained, the main findings are:

— The sequence and the order of the faces to see the banknote are very interesting.

— The heat map is substantially different from that of phase 1.

— The front and reverse motif and hologram are the most visited and revisited areas of the banknote. This is the same as in phase 1.

— The order of watching always starts on the main motif front. This is the same as in phase 1.

— The hologram has a high rate of visits and it is second in terms of being watched for the first time, similar to phase 1.

— The transparent window is visited especially on the front side.

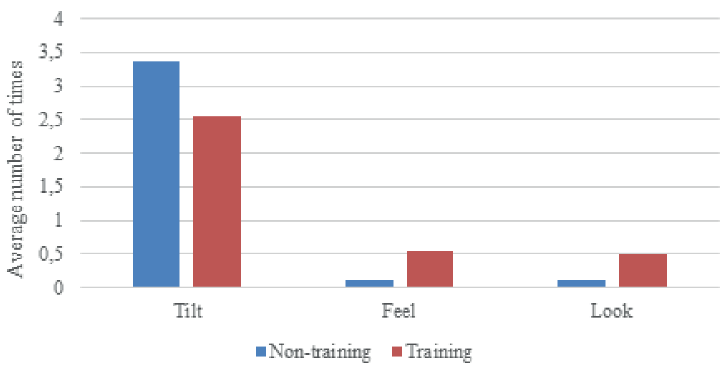
— The tactile printed effect on the right of the banknote has been much more visited than in phase 1.

5.2.3 Human Behaviour Tracking: gesture analysis

These metrics have been extracted in order to ascertain the behaviour of the user at the level of manipulation of banknotes. Gestures have been tabulated and encoded from the video recorded with the eye tracking glasses. The registered movements are those based on the three-step verification, namely “feel, look and tilt”. These three steps are essential to detect the security elements included in a banknote. Chart 9 presents the data extracted from this analysis.

Significantly, the most common behavioural gesture is to tilt the banknote. It is the most intuitive movement when checking a banknote. Significant differences are found between the group that has received training and that which has not, the latter being that which presents higher values of the tilt metric, logically because it is a more natural

Chart 9
AVERAGE OF GESTICULATIONS IN PHASE 2



SOURCES: Banco de España and LENI.
NOTE: Comparison of gestures detected during manipulation of banknotes between people that received training and people who did not receive training. Asterisk (*) in comparisons with significant differences (p<.05).

and intuitive gesture. However, the trained group presents higher metrics of the feeling and looking gestures, since they are performed to a lesser extent spontaneously. Notably, a fold gesture has also been detected during this study. This is interesting to take into account in subsequent studies, but it not significant in the study at hand.

In summary, training can be affirmed to be necessary when it comes to knowing the security elements that are included in a banknote.

6 Conclusions

This study confirms that the neurometric methodology in question is an improvement in the field of banknote and security feature design. To accomplish this goal, a set of three elements have been used: a methodology to analyse the design and the security features of banknotes; hardware to capture all the information signals; and software to calculate the algorithms of the methodology and to obtain the data.

The results show that the visual engagement depends on both evaluation phases (visual and physical). In the visual evaluation, the participant's attention focuses on the aesthetics of the design. However, during the physical evaluation the participants concentrate more on the security elements and the substrate of the banknote. The use of eye tracking, electroencephalography and facial expression analysis allow us to obtain both visual tracking, engagement level, emotions and workload metrics of each banknote's area of interest, with which a banknote behavioural map can be made.

Therefore, a methodology based on both evaluation phases is interesting for the banknote neurodesign process, as each phase provides different information on the participant's assessment that it is impossible to acquire from just a questionnaire. This is demonstrated by the fact that the neuroadvance metrics show a low correlation with the results obtained from participant's explicit responses in the questionnaires. This does not invalidate the explicit responses, but it shows that the future work on banknotes design has to be based on neurometrical studies, complemented by questionnaires.

In addition, dependency on the gender and age of the participant, whether they usually handle cash and whether they have been trained in banknote security features, the results suggest that a balanced participant sample should be selected to obtain representative results.

In conclusion, the way has been paved to consider neurometrics as a rigorous scientific procedure to impartially obtain the public perception of banknotes. This powerful and versatile methodology will thus be used for the neurodesign of banknotes and the integration of security features.

7 Future work

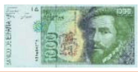
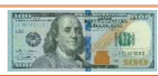
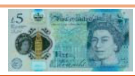
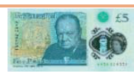
This work is an avenue of research carried out by the Banco de España and the Universitat Politècnica de Valencia. In the future, there will be additional publications based on our further research into neurodesign for banknotes and security features. Additionally, the patent on “Method and system of classification of banknotes based on Neuroanalysis”, registered in June 2019 by the Banco de España, is under review by the Spanish Patent and Trademark Office.

The developments in Neurometrics applied to the design of banknotes and security elements by the Banco de España and Universitat Politècnica de Valencia R&D team will continue, especially a new kit equipped with artificial intelligence to process the information gathered via supervised machine learning algorithms obtaining representative assessments of the public’s perception about banknote and security feature design. In particular, it is planned to pursue studies on new security features for banknotes and new banknotes, including concept banknotes elaborated in the initial stages of new banknote series.

Collaborations with the ECB / NCBs and other partners are also envisaged to apply this methodology for the neurodesign of banknotes and security features.

Appendix A Banknote Front and back images

Table A.1
BANKNOTE FRONT AND BACK IMAGES

	Currency	Denomination	Front image	Back image
Euro banknotes	Euro	5 (First Series)		
	Euro	5 (Europa Series)		
	Euro	50 (First Series)		
	Euro	50 (Europa Series)		
	Euro	200 (First Series)		
European paper banknotes prior to euro	Peseta	1,000		
	Guilder	25		
International paper banknotes	Yuan	20		
	Yen	1,000		
	Swiss franc	20		
	Bolivar	5,000		
	Ruble	100		
	Rand	10		
	US dollar	100		
International polymer banknotes	Guarani	2,000		
	New Zealand dollar	10		
	Pound sterling	5		
Manufacturer banknote sample	Koening & bauer	No value		

SOURCE: Banco de España.

Appendix B Common areas of the banknotes

Table A.2

COMMON AREAS OF THE BANKNOTES

Areas or elements relating to banknote design	Security elements of the banknotes
Substrate	Watermark
Currency	Security thread
Country	Special inks
Issuer	Hologram
Face value	Transparent windows
Year	Rainbow printing
Type (ordinary or commemorative banknote or manufacturer's sample)	See-through register
In circulation	Latent image
Main motif front	Microprintings
Main motif reverse	Tactile printed effect
Size (Banknote dimensions appreciated as an attribute, i.e. Big/small, proportionate/ disproportionate)	Applied element
Front orientation	Serial number
Reverse orientation	
Predominant colour	
Common element	
Coat of arms or symbol	
Signatures	
Copyright	

SOURCE: Banco de España.

Appendix C Questionnaires

Table A.3
QUESTIONNAIRES

	Identifiable		Traditional		Colours		Images		Connotations		Confusion		Recognise Value		Recognise Country	
Banknote	Mean	Ds	Mean	Ds	Mean	Ds	Mean	Ds	Mean	Ds	Mean	Ds	Mean	Ds	Mean	Ds
1000 ESP	4,59	1,02	4,29	1,12	3,71	1,34	3,69	1,19	3,14	1,43	1,69	1,10	4,71	0,99	4,67	1,05
1000 JPY	4,00	1,25	4,19	1,21	2,77	1,35	3,26	1,27	3,17	1,40	2,05	1,35	4,08	1,38	3,95	1,46
100 USD	4,49	1,07	4,29	1,09	2,63	1,37	3,47	1,26	3,73	1,38	1,80	1,14	4,65	1,08	4,67	1,10
100 RUB	3,27	1,43	2,02	1,23	3,72	1,22	2,86	1,40	2,33	1,31	2,76	1,52	3,35	1,61	2,25	1,56
10 NZD	4,08	1,13	3,48	1,24	4,13	1,15	3,76	1,13	2,60	1,35	1,88	1,22	4,19	1,32	4,42	1,22
10 ZAR	4,26	1,17	3,38	1,28	3,92	1,18	3,88	1,21	3,97	1,23	1,97	1,26	3,99	1,44	4,69	0,86
2000 PYG	4,04	1,15	3,72	1,29	3,23	1,32	3,07	1,31	3,99	1,22	2,33	1,34	4,17	1,33	4,49	1,18
200 EUR	4,55	1,08	3,16	1,34	3,47	1,55	3,59	1,33	2,43	1,36	1,83	1,30	4,67	1,13	4,51	1,31
20 CHF	3,24	1,48	2,27	1,19	3,50	1,53	2,89	1,34	2,51	1,36	3,00	1,57	3,56	1,59	3,45	1,67
20 CNY	4,19	1,13	4,01	1,20	3,26	1,33	3,39	1,19	4,06	1,22	1,96	1,23	4,00	1,43	4,01	1,45
25 NLG	2,54	1,51	1,48	0,92	3,35	1,52	2,45	1,34	1,92	1,13	3,52	1,62	3,11	1,72	2,89	1,72
5000 VEF	4,05	1,26	3,23	1,37	3,70	1,36	3,37	1,33	2,89	1,31	2,12	1,37	4,16	1,36	4,47	1,32
50 EUR	4,65	0,91	3,57	1,17	3,23	1,32	3,65	1,20	2,68	1,42	1,62	1,07	4,82	0,78	4,60	1,15
50 EUR Europa	4,64	0,88	3,31	1,26	3,43	1,31	3,76	1,12	2,53	1,39	1,57	1,04	4,88	0,71	4,61	1,15
5 EUR	4,61	1,09	3,56	1,33	3,03	1,47	3,71	1,25	2,37	1,35	1,66	1,19	4,75	1,01	4,60	1,20
5 EUR Europa	4,57	1,26	3,57	1,38	2,87	1,44	3,59	1,32	2,38	1,48	1,69	1,19	4,74	1,10	4,51	1,37
5 GBP	4,62	0,89	4,32	1,11	3,57	1,20	3,77	1,22	3,99	1,26	1,95	1,26	4,61	1,00	4,82	0,87
KBA	3,13	1,49	2,97	1,41	3,47	1,35	2,83	1,30	3,06	1,32	3,31	1,55	2,29	1,57	1,68	1,15

SOURCES: Banco de España and LENI.

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References

Amodio, D. M., E. Harmon-Jones and P. G. Devine (2003). "Individual differences in the activation and control of affective race bias as assessed by startle eyeblink response and self-report", *Journal of Personality and Social Psychology,* Vol. 84, No. 4, April, pp. 738-753.

Bagozzi, R. P., and W. J. M. I. Verbeke (2014). "Biomarketing: an emerging paradigm linking neuroscience, endocrinology, and genetics to buyer–seller behaviour", *The Routledge Companion to the Future of Marketing,* Routledge.

Banse, R. (1999). "Automatic evaluation of self and significant others: affective priming in close relationships", *Journal of Social and Personal Relationships,* Vol. 16, No. 6, December, pp. 803-821.

Bechara, A., and A. R. Damasio (2005). "The somatic marker hypothesis: A neural theory of economic decision", *Games and Economic Behaviour,* Vol. 52, No. 2, August, pp. 336-372.

Becker, W. J., R. Cropanzano and A. G. Sanfey (2011). "Organizational neuroscience: Taking organizational theory inside the neural black box", *Journal of Management,* Vol. 37, No. 4, February, pp. 933-961.

Berka, C., D. J. Levendowski, M. N. Lumicao, A. Yau, G. Davis, V. T. Zivkovic, R. E. Olmstead, P. D. Tremoulet and P. L. Craven (2007). "EEG correlates of task engagement and mental workload in vigilance, learning, and memory tasks", *Aviation, Space, and Environmental Medicine,* Vol. 78, No. 5, Supplement 1, May, pp. 231-244.

Blanco-Velasco, M., B. Weng and K. E. Barner (2008). "ECG signal denoising and baseline wander correction based on the empirical mode decomposition", *Computers in Biology and Medicine,* Vol. 38, No. 1, January, pp. 1-13.

Brief, A. P. (1998). *Foundations for organizational science. Attitudes in and around organizations,* Sage Publications, Inc.

Chicchi Giglioli, I. A., G. Pravettoni, D. L. Sutil Martín, E. Parra and M. A. Raya (2017). "A novel integrating virtual reality approach for the assessment of the attachment behavioural system", *Frontiers in Psychology,* Vol. 8, June, p. 959.

Clifford, G. D., F. Azuaje and P. Mcsharry (2006). *Advanced Methods and Tools for ECG Data Analysis,* Artech House, Inc.

Cunningham, W. A., C. L. Raye and M. K. Johnson (2004). "Implicit and Explicit Evaluation: fMRI correlates of valence, emotional intensity, and control in the processing of attitudes", *Journal of Cognitive Neuroscience,* Vol. 16, No. 10, March, pp. 1717-1729.

Davidson, R. J. (2004). "What does the prefrontal cortex 'do' in affect: perspectives on frontal EEG asymmetry research", *Biological Psychology,* Vol. 67, No. 1-2, October, pp. 219-233.

De Heij, H. (2015). "The Coaster-model. Defining user functions of a banknote", *IBDA Insight,* Vol. 10, November, pp. 31-34.

Diego-Más, J. A., and J. Alcaide-Marzal (2014). "Using Kinect™ sensor in observational methods for assessing postures at work", *Applied Ergonomics,* Vol. 45, No. 4, July, pp. 976-985.

Fazio, R. H., and T. Towles-Schwen (1999). "The MODE model of attitude-behaviour processes", in S. Chaiken and Y. Trope (Eds.), *Dual-process theories in social psychology,* Guilford Press, pp. 97-116.

Feise, R. J. (2002). "Do Multiple Outcome Measures Require P-Value Adjustment?", *BMC Medical Research Methodology,* Vol. 2, June, article 8.

Glimcher, P. W. (2003). *Decisions, uncertainty and the brain: The science of neuroeconomics,* MIT Press.

Goel, V., and R. J. Dolan (2003). "Reciprocal neural response within lateral and ventral medial prefrontal cortex during hot and cold reasoning", *NeuroImage,* Vol. 20, No. 4, December, pp. 2314-2321.

Greene, J. D., R. B. Sommerville, L. E. Nystrom, J. M. Darley and J. D. Cohen (2001). "An fMRI investigation of emotional engagement in moral judgment", *Science,* Vol. 293, No. 5537, September, pp. 2105-2108.

Greenwald, A. G., and M. R. Banaji (1995). "Implicit social cognition: attitudes, self-esteem, and stereotypes", *Psychological Review,* Vol. 102, No. 1, January, pp. 4-27.

Guixeres, J., E. Bigné, J. M. A. Azofra, M. A. Raya, A. C. Granero, F. F. Hurtado and V. Naranjo (2017). "Consumer Neuroscience-based metrics predict recall, liking and viewing rates in online advertising", *Frontiers in Psychology,* Vol. 8, October, p. 1808.

Klein, R. M., S. Gadbois and J. J. Christie (2004). "Perception and detection of counterfeit currency in Canada: note quality, training, and security features", *Proceedings SPIE,* Vol. 5310, Optical Security and Counterfeit Deterrence Techniques V.

Knyazev, G. G., J. Y. Slobodskoj-Plusnin and A. V. Bocharov (2009). "Event-related delta and theta synchronization during explicit and implicit emotion processing", *Neuroscience,* Vol. 164, No. 4, December, pp. 1588-1600.

Kopton, I. M., and P. Kenning (2014). "Near-infrared spectroscopy (NIRS) as a new tool for neuroeconomic research", *Frontiers in Human Neuroscience,* Vol. 8, August, p. 549.

Krause, S., M. D. Back, B. Egloff and S. C. Schmukle (2016). "Predicting Self-Confident Behaviour with Implicit and Explicit Self-Esteem Measures", *European Journal of Personality,* Vol. 30, No. 6, October, pp. 648-662.

Lane, R. D. (2008). "Neural substrates of implicit and explicit emotional processes: a unifying framework for psychosomatic medicine", *Psychosomatic Medicine,* Vol. 70, No. 2, February-March, pp. 214-231.

Lanyon, R. I., and L. D. Goodstein (1997). *Personality Assessment,* John Wiley & Sons.

Masuda, O., M. Pedersen and J. Y. Hardeberg (2015). "Effects of awareness to security features on the confidence in banknotes", *Journal of Print and Media Technology Research,* Vol. 4, No. 2, June, pp. 103-110.

Milosavljevic, M., V. Navalpakkam, C. Koch and A. Rangel (2012). "Relative visual saliency differences induce sizable bias in consumer choice", *Journal of Consumer Psychology,* Vol. 22, No. 1, January, pp. 67-74.

Nikula, R. (1991). "Psychological correlates of nonspecific skin conductance responses", *Psychophysiology,* Vol. 28, No. 1, January, pp. 86-90.

Nisbett, R. E., and T. D. Wilson (1977). "Telling more than we can know: verbal reports on mental processes", *Psychological Review,* Vol. 84, No. 3, May, pp. 231-259.

Nosek, B. A., M. R. Banaji and A. G. Greenwald (2002). "Harvesting implicit group attitudes and beliefs from a demonstration web site", *Group Dynamics: Theory, Research, and Practice,* Vol. 6, No. 1, March, pp. 101-115.

Nussbaum, P. A., A. Herrera, R. Joshi and R. Hargraves (2012). "Analysis of viewer EEG data to determine categorization of short video clip", *Procedia Computer Science,* Vol. 12, pp. 158-163.

Ohme, R., D. Reykowska, D. Wiener and A. Choromanska (2010). "Application of frontal EEG asymmetry to advertising research", *Journal of Economic Psychology,* Vol. 31, No. 5, October, pp. 785-793.

Pan, J., and W. J. Tompkins (1985). "A Real-Time QRS Detection Algorithm", *IEEE Transactions on Biomedical Engineering,* Vol. 32, No. 3, March, pp. 230-236.

Panksepp, J. (2005). "On the embodied neural nature of core emotional affects", *Journal of Consciousness Studies,* Vol. 12, No. 8-10, January, pp. 158-184.

Paulhus, D. L. (1991). "Measurement and control of response bias", in J. P. Robinson, P. R. Shaver and L. S. Wrightsman (Eds.), *Measures of social psychological attitudes,* Vol. 1, *Measures of personality and social psychological attitudes,* pp. 17-59.

Piqueras-Fiszman, B., C. Velasco, A. Salgado-Montejo and C. Spence (2013). "Using combined eye tracking and word association in order to assess novel packaging solutions: A case study involving jam jars", *Food Quality and Preference,* Vol. 28, No. 1, April, pp. 328-338.

Raya M. A., E. Parra and I. A. Chicchi Giglioli (2018). "Virtual reality as an emerging methodology for leadership assessment and training", *Frontiers in Psychology,* Vol. 9, September, p. 1658.

Rebollar, R., I. Lidón, J. Martín and M. Puebla (2015). "The identification of viewing patterns of chocolate snack packages using eye-tracking techniques", *Food Quality and Preference,* Vol. 39, January, pp. 251-258.

Rodríguez, A., B. Rey, M. Clemente, M. Wrzesien and M. Alcañiz (2015). "Assessing brain activations associated with emotional regulation during virtual reality mood induction procedures", *Expert Systems with Applications,* Vol. 42, No. 3, February, pp. 1699-1709.

Schmitt, N. (1994). "Method bias: The importance of theory and measurement", *Journal of Organizational Behaviour,* Vol. 15, No. 5, September, pp. 393-398.

Shao, E., and B. S. C. Fung (2016). "Counterfeit quality and verification in a monetary exchange", *Economic Modelling,* Vol. 52, Part A, January, pp. 13-25.

Spence, C., C. Velasco and K. Knoeferle (2014). "A large sample study on the influence of the multisensory environment on the wine drinking experience", *Flavour,* Vol. 3, No. 8, October, pp. 1-12.

Vecchiato, G., L. Astolfi, F. D. V. Fallani, F. Cincotti, D. Mattia, S. Salinari, R. Soranzo and F. Babiloni (2010). "Changes in brain activity during the observation of TV commercials by using EEG, GSR and HR measurements", *Brain Topography,* Vol. 23, December, pp. 165-179.

Vecchiato, G., A. G. Maglione, P. Cherubino, B. Wasikowska, A. Wawrzyniak, A. Latuszynska, M. Latuszynska, K. Nermend, I. Graziani, M. R. Leucci, A. Trettel and F. Babiloni (2014). "Neurophysiological tools to investigate consumer gender differences during the observation of TV commercials", *Computational and Mathematical Methods in Medicine,* July, pp. 1-12.

Venkatraman, V., A. Dimoka, P. A. Pavlou, K. Vo, W. Hampton, B. Bollinger, H. E. Hershfield, M. Ishihara and R. S. Winer (2015). "Predicting Advertising Success Beyond Traditional Measures: New Insights from Neurophysiological Methods and Market Response Modeling", *Journal of Marketing Research,* Vol. 52, No. 4, August, pp. 436-452.

Waldmans, D. A., and P. A. Balthazard (2015). *Organizational Neuroscience,* Emerald Group Publishing Limited.

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