Review Article

Cite this article: Borgianni Y, Maccioni L (2020). Review of the use of neurophysiological and biometric measures in experimental design research, Artificial Intelligence for Engineering Design, Analysis and Manufacturing 34, 248–285; https://doi.org/10.1017/S0890060420000062

Received: 4 February 2019
Revised: 14 November 2019
Accepted: 14 November 2019
First published online: 11 February 2020

Key words:
Biometric versus traditional measures; design cognition; electroencephalography; eye-tracking; product evaluation

Author for correspondence:
Yuri Borgianni, E-mail: yuri.borgianni@unibz.it

Abstract

Design is inherently affected by human-related factors and it is of no surprise that the fine-tuning of instruments capable of measuring aspects of human behavior has attracted interest in the design field. The recalled instruments include a variety of devices that capture and quantitatively assess people’s unintentional and unconscious reactions and that are generally referred as neurophysiological or biometric. The number of experimental applications of these instruments in design was extremely limited as of 2016, when Lohmeyer and Meboldt published a first report on relevant measures and their interpretation in design. In the last few years, the number of relevant publications has increased dramatically and this determines the opportunity to carry out a comprehensive review in the field. The reviewed contributions are analyzed and classified according to, among others, instruments used, the kind of stakeholders involved and the supported design research activities. The role of biometric measures with respect to traditional research methods is emphasized too. The discussed instruments can represent supports or substitutes for traditional approaches, as well as they are capable of exploring phenomena that could not be addressed hitherto. The intensity of research concerning experiments with biometric measurements is discussed too; a particular focus of the final discussion is the individuation of obstacles that prevent them from becoming commonplace in design research.

Introduction

Human factors are considered of paramount importance in design practice and research, although their unpredictability represents an obstacle to the creation of models that include individuals in the design process (Papalambros, 2010). At the same time, design research is increasingly requested to include objective measures that characterize its inherent phenomena, e.g. (Dinar et al., 2016) – this is particularly critical when human-related aspects are involved. In addition, scholars long for alleviating the burden of some human-intensive activities in design and design research and making these processes more automated – a case in point is protocol analysis (Jiang and Yen, 2009).

These considerations might well represent triggers for supporting design research with instruments capable of capturing, measuring, quantifying and interpreting inadvertent, unconscious and involuntary features of human behavior (Lohmeyer and Meboldt, 2016). Those instruments include neurophysiological (Balters and Steinert, 2017) and neuropsychological (Steinert and Jablokow, 2013) devices, which are mainly oriented to neuroimaging or to measure brain activities. A broader set of instruments is often referred to as biometric devices (Lohmeyer and Meboldt, 2016), whose measures deal with a larger variety of biological indexes beyond those ascribable to the brain. The term “biometric” will be used in the present paper when discussing this class of devices and measures in very general terms. Collections of the specific devices enabling biometric measurements deemed useful in design and engineering are available in Lohmeyer and Meboldt (2016), Balters and Steinert (2017), and Peruzzini et al. (2017).

The present contribution is concerned with the understanding of how, to which extent and in which specific domains, biometric instruments have shaped design research. The previous literature has collected illustrative examples of design-oriented applications of biometric instruments to introduce readers to the field (Lohmeyer and Meboldt, 2016; Balters and Steinert, 2017). Other articles have broadly discussed the potential of biometric devices in design, presented research methods, laboratories and infrastructure to use biometric instruments effectively, or pinpointed the scope of their employment. Overall, the emerged potential objectives of their exploitation in design and motivations for their diffusion can be summarized as in the followings.

© Cambridge University Press 2020. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted re-use, distribution, and reproduction in any medium, provided the original work is properly cited.
• The study of designers’ cognition, cognitive states (Mougenot et al., 2009) and emotions (Zhao et al., 2017).

• The inclusion of concepts from affective engineering (Balters and Steinert, 2017), emotional and Kansei engineering (Hsu et al., 2017; Zhao et al., 2017), so as to foster emotional design (Triberti et al., 2017) or beauty through design (Khalighy et al., 2015).

• The support of traditional methods by opening up new avenues in the understanding of usability (Hill and Bohil, 2016), user-product interaction (Jenkins et al., 2009; Balters and Steinert, 2017; Mussgnug et al., 2017), user experience (Mussgnug et al., 2014; Jiao et al., 2017), and user intent (Yang et al., 2016). These are supposed to play an increasing role in design, for instance due to the growing emphasis attributed to human-centered design.

• The evaluation and benchmark of new products and designs by means of unconscious feedback (Abdipour et al., 2016), the individuation of points and determinants of attraction (Zhang et al., 2014; Georgiev et al., 2017), or the understanding of the psychology of customers (Wang et al., 2011).

While objectives and possible benefits of biometric measurements in design have been pinpointed, previous literature has failed to treat the topic in a comprehensive way. This applies particularly to the results and implications of practical experiments, which are systematically reviewed in the present paper. It is also worth noting that the growing number of literature contributions published in the last few years, as the outcomes of the study will elucidate, would have made previous attempts invalid. For instance, the first overview presented in Lohmeyer and Meboldt (2016) described the work of few pioneering research groups active before 2016. In the authors’ view, the topic is mature and relevant enough for a first state-of-the-art analysis; the following reasons support this thought in addition to the recalled relatively large number of recent publications.

• Some scientific events have been organized in the last few years, which demonstrate that the interest in the topic is not restricted to pioneering groups anymore.

• As the treated technologies are now available at generally accessible costs, they have higher chances to become commonplace in design research in the near future.

Accordingly, the present paper intends to gather, benchmark and illustrate experiments and hands-on studies, their results, design implications, alignment with the aforementioned objectives. The paper is organized as follows. The second section presents the steps followed to create a comprehensive sample of relevant experiments. These experiments are first classified into two main groups: experiments involving product evaluation and design processes, whose objectives and main characteristics are illustrated in the third and fourth sections, respectively. The fifth section discusses the outcomes in a qualitative and quantitative way and indicates the limitations of the present study. Conclusions are drawn in the final section.

Sample of reference studies to be analyzed and fundamental classification means

As the goal of the study is to analyze previous research on the use of biometric instruments in design, the first activity was constituted by the collection of reference literature contributions. This took place by collecting the contributions the authors already knew, a snowballing process to individuate additional relevant examples in backward and forward citations, and a final literature search in which the Scopus database was used. This search was carried out by using the field “Title, Abstract and Keywords”, in which terms belonging to both the two groups below should appear.

1. A group of terms ascribable to the design domain, for example “design” or “product development”.

2. A group of terms addressing the ways the instruments in question are referred, for example “biometric” or “physiological”; the name of devices or their common acronyms, for example “eye-tracking”, “electroencephalography”, or “EEG”; or the measures that are extracted, for example “gaze event”, “blood pressure”, or “skin conductance”.

Only those articles describing experiments (claiming to be) relevant to design were further considered. Many contributions were excluded because, despite the matching of search terms in Scopus, were devoted to domains such as “human–machine interaction” or “human–computer interaction”. These domains, beyond not being included within traditional design fields, [see Dykes et al. (2009)], do not mirror the objectives of the use of biometric measures listed in the “Introduction” section. For instance, in human–computer interaction, the use of biometric devices is predominantly oriented to the use of data for allowing computerized systems to work, e.g. for the support of disabled users. In other words, biometric measures do not serve the need of improving design processes or deliverables, which is the fundamental objective for their introduction in engineering and product design, among others. Some articles were excluded because the same experiment with akin measurements was presented in different sources, e.g. a journal extended version of a conference paper – here, the most recent and complete version was considered further.

The final list of analyzed papers is available in Table 1. The table (second column) includes a first classification according to the role played by people participating in the experiment and subjected to biometric measurements, namely evaluators and designers. The former have the task of evaluating products or any deliverables of design processes in order to provide information relevant to design itself; for instance, such information regards understandability of the designs, assessment of quality or attractiveness, and hints useful to form consumer preferences. The latter actively participate in the design process and have to perform tasks that are ascribable to designers, e.g. ideating or making decisions. In light of this distinction, the second group is more oriented to design research than the first one, which is conversely majorly featured by an interest in design deliverables. The same distinction between evaluators and designers, which is made explicit already in Lohmeyer and Meboldt (2016), is also used to subdivide the following two sections.

In the fourth column, Table 1 reports the biometric tools that are used in the experiments described in the corresponding contributions. As inferable from the table, the following biometric and neurophysiological devices have been overall used.

• Eye-tracking (ET) devices meant to acquire one’s visual patterns and pupil diameter. The two models, that is remote ET and ET glasses (sometimes referred to as mobile ET), are used when...
| Source of the experiment | Role of participants | Kind of experiment | Biometric Tool | Corresponding measure or analysis method | Definition or relevant indications (excerpt from the source) | Connected variables or interpreted phenomenon | Inverse Relationship | Nature of the relationship |
|--------------------------|----------------------|--------------------|---------------|------------------------------------------|----------------------------------------------------------|-----------------------------------------------|----------------------|---------------------------|
| Alexiou et al. (2009)    | Designers            | Alternative        | fMRI          | Activation of the cerebellum and the Brodmann Areas: 6, 3, 1, and 2 | Freedom of the task performed (design vs. problem-solving) | Observed                                      |                      |                           |
|                         |                      |                    |               | Activation of the Brodmann Areas: 10, 9 Right, 46, 18, 25, 24 Left, 32 Right, 21 Right, 8 Right, 13 | Freedom of the task studied (design vs. problem-solving) | Observed                                      |                      |                           |
|                         |                      |                    |               | Activation of the Brodmann Areas: 32, 46, and 9 | Cognitive effort | Observed                                      |                      |                           |
| Aurup and Akgunduz (2012)| Evaluators           | Confirmation of hypotheses | EEG           | Alpha-peak value in channels F3 and F4 | Preference | Proven                                      |                      |                           |
| Bi et al. (2015)         | Designers            | Confirmation of hypotheses | Remote ET     | Percentage total duration of fixations | Fixation time within one AOI divided by the whole period time | Graphical content in information (graphic vs. numerical) | Assumed              |                           |
| Boa and Hicks (2016)     | Designers            | Alternative        | Remote ET     | SF Ratio | Saccade amplitude divided by fixation duration | Processing time (of a stimulus) | Assumed              |                      |
| Boa et al. (2013)        | Evaluators           | Additional data    | Remote ET     | Normalized total duration of fixations | The Total Fixation Duration for every AOI was normalized for each participant | Engagement | Assumed              |                      |
| Boa et al. (2015)        | Evaluators           | Confirmation of hypotheses | Remote ET     | Duration of fixations and average total duration of fixations | Engaged | Assumed                                      |                      |                           |
|                         |                      |                    |               | Dwell time | The total time spent fixating within an AOI, is normalized for each AOI as a percentage of total scene viewing time | Importance (placed on a product feature) | Assumed              |                      |
| Borgianni et al. (2019)  | Evaluators           | Additional data    | ET glasses    | Total number of fixations | Exploration (aimed to make sense of objects) | Assumed                                      |                      |                           |
|                         |                      |                    |               | Number of interactions | Number of times participant look (continuously) at the product | Assumed                                      |                      |                           |
|                         |                      |                    |               | Number of fixations and total duration of fixations during interactions | Assumed                                      |                      |                           |
|                         |                      |                    |               | Number of fixations and saccades and total duration of | Impact (of a product) | Assumed                                      |                      |                           |
| Authors | Roles       | Methodology                                      | Measures                                                                 | Notes                  |
|---------|-------------|--------------------------------------------------|---------------------------------------------------------------------------|------------------------|
| Burlamaqui and Dong (2017) | Evaluators  | Confirmation of hypotheses                        | Average pupil diameter, Number of long-duration fixations, Number of fixations | Assumed, Not Proven    |
|         |             | Remote ET                                        | Correctness of perception (intended affordances), Effort (spent in cognitive processes) |                       |
| Cao et al. (2018) | Designers  | Additional data                                  | Percentage total duration of fixations in a specific AOI, It is the fixation time spent on a domain divided by the total fixation time spent on the three domains (considered in the paper), Attention (paid to a specific stimulus in idea generation) | Assumed                |
|         |             | Remote ET                                        | Presence of a processing behavior (between different distance source domains), Presence of a comparing behavior (between objects featuring close analogical distance) | Assumed                |
| Carbon et al. (2006) | Evaluators  | Exploration of links                             | AOI fixated first, Difference in density of fixations between AOIs, Average pupil diameter | Observed               |
|         |             | Remote ET                                        | Innovativeness (of features), X, Characterization of participant's background |                       |
| Colaço and Acartürk (2018) | Designers  | Alternative                                        | Total duration of fixations and Mean duration of fixations, Measures the duration of each individual fixation within an AOI, Total dwell time and Mean dwell time | Observed               |

(Continued)
| Source of the experiment | Role of participants | Kind of experiment | Biometric Tool | Corresponding measure or analysis method | Definition or relevant indications (excerpt from the source) | Connected variables or interpreted phenomenon | Inverse Relationship | Nature of the relationship |
|-------------------------|----------------------|-------------------|---------------|------------------------------------------|-------------------------------------------------------------|-------------------------------------------------|----------------------|-------------------------|
| Dogan et al. (2018)     | Evaluators           | Exploration of links | Remote ET     | Normalized total duration of fixations   | Fixation durations are standardized to be relative to the time periods of subjects and the sizes of AOIs for each design parameter | Attractiveness (of target areas)               | Assumed              |
|                         |                      |                   |               |                                         |                                                             |                                                 |                      |
|                         |                      |                   |               | Normalized dwell time on AOIs           |                                                             |                                                 |                      |
|                         |                      |                   |               | Transition count and probability        | The transition counts *(in a specific AOI)* are divided by total transitions made, and the results are interpreted as transition probability | Assumed                                          |
|                         |                      |                   |               | Time to first fixation                  | *It indicates* the time spent before the subjects’ first attention for a target AOI | Assumed                                          |
| Du and MacDonald (2014) | Evaluators           | Confirmation of hypotheses | Remote ET     | Number and total duration of fixations   | Importance and noticeability (of a feature) | Proven                                           |
|                         |                      |                   |               | Percentage total duration of fixations and Mean total duration of fixations | *It is the fixation time spent on an AOI divided by the total fixation time spent on the stimulus* | Importance (of a feature)                      | Proven |
|                         |                      |                   |               | Time to first fixation and Mean Time to first fixation | *It is a measurement of the time between initial exposure to a stimulus and first fixation on that AOI* | Proven                                           |
|                         |                      |                   |               | Mean Delta of total duration and number of fixations | Difference among different designs | Noticeability (of a feature) | Proven |
| Du and MacDonald (2015) | Evaluators           | Additional data   | Remote ET     | Number and total duration of fixations   | Uniqueness (of product attributes/features in a comparison activity) | Not Proven                                      |
| Du and MacDonald (2018) | Evaluators           | Additional data   | Remote ET     | Percentage total duration of fixations   | Presence of cues (in pictures’ AOIs for specific tasks) | Proven                                           |
| Origin                          | Group             | Additional data | Method | Description                                                                 | Assumption |
|--------------------------------|-------------------|-----------------|--------|-----------------------------------------------------------------------------|------------|
| Ergan et al. (2019)            | Evaluators       | Additional data | GSR    | Skin Conductance Response (SCR) peaks (number/minute and amplitude)          | Assumed    |
|                                |                   |                 |        | SCR signal jump higher than the defined threshold (i.e., onset amplitude)   |            |
|                                |                   |                 |        | Emotional and Stress response                                               |            |
| EEG                            |                   |                 |        | Algorithm capable of processing the power spectrum to obtain emotional responses | Assumed    |
|                                |                   |                 |        | A power spectrum diagram shows EEG signals in the frequency domain and describes the distribution of power in frequency bands |            |
|                                |                   |                 |        | Frustration, engagement, excitement, stress, and anxiety                    |            |
| HRV                            |                   |                 |        | Inter-beat interval through Average normal sinus to normal sinus interval (AVNN score) | Assumed    |
|                                |                   |                 |        | The time between consecutive heart beats. Average of the normal sinus (i.e., heart rate of 60–100 beats per minute) intervals |            |
|                                |                   |                 |        | Stress                                                                      |            |
| Goucher-Lambert et al. (2018)  | Designers        | Additional data | fMRI   | Activation of the Brodmann Areas: 22, 21, 39 Right, 7, 31                  | Observed   |
|                                |                   |                 |        | Inspirational capability (in stimuli)                                      |            |
|                                |                   |                 |        | Analogical distance (in stimuli)                                           | X          |
|                                |                   |                 |        | X Observed                                                                  |            |
|                                |                   |                 |        | Activation of the Brodmann Areas: 13 Left, 41 Left, 24, 21, 38 Right, 3 left, 4 Left, and 22 Left |            |
|                                |                   |                 |        | X Observed                                                                  |            |
|                                |                   |                 |        | Activation of the Brodmann Areas: 18, 19, 8, 9, 32, 31, 24                 | X          |
|                                |                   |                 |        | X Observed                                                                  |            |
|                                |                   |                 |        | Activation of the cerebellum and Brodmann Areas: 9, 32, 30, 19, 18, 6 Right, 39 Left, and 40 Left | X          |
|                                |                   |                 |        | Success of a task (in a search for solutions)                              |            |
| Guo et al. (2016)              | Evaluators       | Exploration of links | Remote ET | Time to first fixation                                                     | Proven     |
|                                |                   |                 |        | Time elapsed from the start of the product displayed until the participant fixated on the AOI for the first time |            |
|                                |                   |                 |        | User experience                                                             | X          |
|                                |                   |                 |        | Total duration of fixations  Duration of all fixations within an AOI       | Proven     |
|                                |                   |                 |        | Number of fixations  Number of times that a participant fixated on an AOI  | Proven     |
|                                |                   |                 |        | Number of visits  Number of times that a participant returned to an AOI     | Proven     |
|                                |                   |                 |        | Variation of pupil diameter  X Proven                                      |            |
|                                |                   |                 |        | Dwell time  The sum time of fixation and saccade (within an AOI)            | Proven     |
| Source of the experiment | Role of participants | Kind of experiment | Biometric Tool | Corresponding measure or analysis method | Definition or relevant indications (excerpt from the source) | Connected variables or interpreted phenomenon | Inverse Relationship | Nature of the relationship |
|-------------------------|---------------------|--------------------|----------------|------------------------------------------|-------------------------------------------------------------|-------------------------------------------------|---------------------|--------------------------|
| Guo et al. (2019)       | Evaluators          | Exploration of links | Remote ET      | Mean total duration of fixations          | Visual aesthetic                                             | Proven                                           |                     |                          |
|                         |                     |                    |                | Percentage duration of fixation           |                                                             | Proven                                           |                     |                          |
|                         |                     |                    |                | Percentage Dwell time                     |                                                             | Proven                                           |                     |                          |
|                         |                     |                    |                | EEG                                       | Presence of Alpha power in every channel                    | Proven                                           |                     |                          |
|                         |                     |                    |                |                                            | Presence of Gamma power in every channel                    | X                                                | Proven                                           |
| He et al. (2017)        | Evaluators          | Additional data    | Remote ET      | Number of fixations                       | Browsing and searching efficiency                            | X                                                | Assumed                                          |
|                         |                     |                    |                | Time to first fixation and Number of fixations in this time |                                                             | X                                                | Assumed                                          |
| Hess et al. (2017)      | Designers           | Additional data    | ET glasses     | Sequence of AOIs’ observation             | Successful understanding (of working principles of a machine) | Not Proven                                       |                     |                          |
| Ho and Lu (2014)         | Evaluators          | Exploration of links | Remote ET      | Variation of pupil diameter               | Pleasantness                                                 | Proven                                           |                     |                          |
| Hsu et al. (2017)       | Evaluators          | Exploration of links | Remote ET      | Number of fixations                       | Pleasure (in Kansei)                                         | X                                                | Proven                                           |
|                         |                     |                    |                | Duration of fixations                     |                                                             |                                                  |                     |                          |
| Hu and Reid (2018)      | Designers           | Additional data    | EEG            | Activation of channels F2, F3, F4, Cz, C3, C4, POz, P3, P4 | Workload and engagement                                      | Assumed                                          |                     |                          |
| Hurley et al. (2013)    | Evaluators          | Additional data    | ET glasses     | Mean number of fixations                  | Attention (in different product structures)                  | Assumed                                          |                     |                          |
|                         |                     |                    |                |>Total duration of fixations               | It is defined as the number of fixations (measured via a velocity filter with a 30/s point-to-point velocity threshold) on a particular AOI |                                                   | Assumed                                          |
|                         |                     |                    |                | Time to first fixation                     | It is the time (…) a participant spent fixating on a particular AOI |                                                   | Assumed                                          |
|                         |                     |                    |                |                                            | It is the time (…) a participant took to first fixate on an AOI from the time they entered the range of the AOI (2.5 m) |                                                   | X                                               | Assumed                      |
| Reference | Evaluators | Design | Remote ET | Measurements | Contextual Variables | Outcome |
|-----------|------------|--------|-----------|--------------|---------------------|---------|
| Hyun et al. (2017) | Evaluators Alternative Remote ET | Looking probabilities Percentage of fixation duration in an area of interest divided by percentage of total picture area covered by the area of interest | Novelty (of shapes) | Proven |
| Ishak et al. (2015) | Evaluators Additional data Remote ET | Time of first fixation Heat map hotspot Attractiveness | Assumed |
| Khalighy et al. (2015) | Evaluators Alternative ET glasses | Number of fixations Standard deviation of duration of fixations | X Assumed |
| Khalighy et al. (2015) | Evaluators Alternative ET glasses | Number of fixations and density of fixations in a single area | Assumed |
| Khalighy et al. (2015) | Evaluators Alternative ET glasses | Density of fixations among different areas | Assumed |
| Khushaba et al. (2013) | Evaluators Exploration of links EEG | Synchronization between the left and right frontal and occipital regions Change in the EEG power spectrum in channels F3, F4, FC5, FC6, T7, and O1 I | Preference Observed |
| Kim et al. (2016) | Evaluators Exploration of links GSR | SCR The original SCR values were normalized, that is, normalized SCR value = original SCR value/maximum of SCR value Emotional arousal | Proven |
| Köhler et al. (2015) | Evaluators Exploration of links Remote ET | Percentage total duration of fixations in a specific AOI Total duration of fixations in a specific AOI | Impression Assumed |
| Koivunen et al. (2004) | Evaluators Alternative Remote ET | Number of long-duration fixations | Complexity (of a product) Assumed |
| Kovačević et al. (2018) | Evaluators Alternative Remote ET | Time to first fixation The time spent from the stimulus onset until the pictogram was fixated for the first time Noticeability (of a feature) X Assumed |
| Kukkonen (2005) | Evaluators Exploration of links Remote ET | Mean number and duration of fixations | Preference Observed |
| Laohakangvalvit and Ohkura (2017) | Evaluators Exploration of links Remote ET | Dwell time Sum of durations of all eye positions inside an AOI | Observed |
| Source of the experiment | Role of participants | Kind of experiment | Biometric Tool | Corresponding measure or analysis method | Definition or relevant indications (excerpt from the source) | Connected variables or interpreted phenomenon | Inverse Relationship | Nature of the relationship |
|--------------------------|----------------------|--------------------|----------------|------------------------------------------|-------------------------------------------------------------|------------------------------------------------|---------------------|---------------------------|
| Li et al. (2017)         | Evaluators           | Alternative        | ET glasses     | Number of fixations                      | Sum of all fixations inside an AOI                         | Attractiveness (in products with similar complexity) | Observed            |                           |
|                         |                      |                    | EEG            | Not specified                            |                                                             | -                                              | -                   |                           |
| Li et al. (2018)         | Evaluators           | Exploration of links | Remote ET      | Number, duration, and frequency of fixations | Number, amplitude, velocity, and frequency of saccades | Interpretability of styling evaluations | Observed            |                           |
|                         |                      |                    |                |                                         | Number, total duration, and frequency of blinks           | Observed            |                   |
| Liang et al. (2017)      | Designers            | Alternative        | EEG            | Beta power in channels Cz, FT7, FC3, and P8 | Visual attention                                           | Assumed            |                   |
|                         |                      |                    |                | Alpha power in channels Cz, F4, F8, Fz, FCz, F7, and FC3 | Presence of visual association | Assumed            |                   |
|                         |                      |                    |                | Gamma power in channels Cz, Pz, O1, FCz, C4, FT8, FC3, and FT7 | Assumed            |                   |
| Liang et al. (2018)      | Designers            | Alternative        | EEG            | EEG power spectrum (especially in slow alpha band and low gamma band) in every channels | Designer experience (in a conceptual imagination task) | Observed            |                   |
|                         |                      |                    |                | EEG power spectrum (especially in the middle beta band) in the right temporal cluster | Observed            |                   |
|                         |                      |                    |                | EEG power spectrum in the left prefrontal cluster | Observed            |                   |
|                         |                      |                    |                | EEG power spectrum (especially in the low beta, high beta, and low gamma bands) | Observed            |                   |
| Study                  | Role         | Methodology | Measurements | Features | Interpretation |
|-----------------------|--------------|-------------|--------------|----------|----------------|
| Liu et al. (2014)     | Designers    | Alternative | EEG          | Alpha power close to 13 Hz in F3 and F4 | Presence of positive emotions | Assumed |
|                       |              |             |              | Alpha power close to 9–10 Hz in F3 and F5 | Presence of negative emotions |              |
| HRV                   |              |             | Heart Rate   | Presence of positive emotions | Psychological arousal and excitement | Assumed |
| GSR                   |              | Normalized SCR | See Nguyen and Zeng (2017) | Mental arousal | Assumed |
| Liu et al. (2016)     | Designers    | Alternative | EEG          | Beta1, Beta2, Gamma1, and Gamma2 power in channel Fz | Interpretability of ongoing design activities | Observed |
| Liu et al. (2018)     | Designers    | Exploration of links | EEG          | Alpha power | Presence of divergent thinking | Assumed |
|                       |              |             |              | (Theta/Alpha) power | Presence of convergent thinking | Assumed |
|                       |              |             |              | (Beta/(Alpha + Theta)) power | Mental workload | Assumed |
|                       |              |             |              | Alpha power in the channels FP2, FC10, F4, F8, FC2, FC6, C4, T8, CP2, CP6, P4, P8, O2 (Right hemisphere) | Open-endedness of design problems | Observed |
|                       |              |             |              | (Theta/Alpha) power in the channels FP1, FC9, F3, F7, FC1, FCS, C3, T7, CP1, CP5, P3, P7, O1 (Left hemisphere) | | Observed |
|                       |              |             |              | Beta/(Alpha + Theta) power in every channels | | Observed |
| Lohmeyer and Meboldt (2015) | Designers | Additional data | Remote ET | Transition Matrix | Interpretability of cognitive processes (during the interpretation of an engineering drawing) | Proven |
|                       |              |             |              | The cells of such matrices contain the frequencies of direct transitions between AOIs. Although the cells on the diagonal by definition should be empty, they are often used to report the number of saccades within an AOI | | |
|                       |              |             |              | Relationship between the durations of Fixations and | A typical skimming sequence (…) is characterized by short fixations and long saccades. Scrutinizing is characterized by | Proven |
|                       |              |             |              | | | |
| Source of the experiment | Role of participants | Kind of experiment | Biometric Tool | Corresponding measure or analysis method | Definition or relevant indications (excerpt from the source) | Connected variables or interpreted phenomenon | Inverse Relationship | Nature of the relationship |
|------------------------|---------------------|------------------|----------------|-----------------------------------------|--------------------------------------------------|-----------------------------------------------|-------------------|--------------------------|
| **Lohmeyer et al. (2013)** | Designers | Alternative | Remote ET | Heat map hotspot | Visual attention | Assumed | |
| **Lou et al. (2017)** | Evaluators | Exploration of links | EEG | Sample Entropy algorithm | Interpretability of psycho-physiological states | Proven | |
| **Maccioni et al. (2019)** | Evaluators | Additional data | Remote ET | Average and maximum angle of saccades | Presence of a voluntary wide exploration | Assumed | |
| | | | | Average and maximum velocity of saccades | | Assumed | |
| | | | | Maximum and total duration of a saccade | Curiosity | Assumed | |
| | | | | Maximum velocity recorded during the pupils’ dilation and constriction | | Assumed | |
| | | | | Total number of fixations and Maximum duration of a fixation | Presence of information foraging | Assumed | |
| | | | | Average velocity of the pupils’ dilation | | Assumed | |
| **GSR** | | | | Number of times a low, mid+, and high level of emotion has been reached in the Emotion_5 algorithm (CAPTIV software) | Emotional arousal | Assumed | |
| | | | | Number of SCR peaks | Number of positive peaks in the phasic level of the GSR signal with standardized value of the original normally distributed variable higher than 1 and 3 | Effort | Assumed | |
| | | | | Number of times a mid level of emotion has been reached in | | Assumed | |
| Authors                  | Designers/Evaluators | Alternative | Methodology | EEG/Hand | Cognitive load | Visual attention | Interpretability of visual behavior | Ease of use | Likelihood of purchasing a product | Presence of an evaluation task (vs. the formulation of a solution to a design problem) | Creativity (of designers' thinking) | Conceptual clarity | Effort | Creativity (in a design task) | Mental effort | Presence of an evaluation task (vs. the formulation of a solution to a design problem) | Presence of an evaluation task (vs. the formulation of a solution to a design problem) |
|-------------------------|----------------------|-------------|-------------|----------|----------------|-----------------|------------------------------------|------------|---------------------------------|------------------------------------------------------------------|----------------------------------|--------------------|--------|----------------------------|-----------------|------------------------------------------------------------------|------------------------------------------------------------------|
| Majdic *et al.* (2017)  | Designers            | Alternative | EEG         | (Theta power/Alpha) power in channels C3–C4, Cz–PO, F3–Cz, Fz–C3, and Fz–PO | Cognitive load | Assumed         |                     |                         |                                |                                    |                                   |                                |                 |                             |                 |                                    |                                    |
| Mussgnug *et al.* (2014)| Evaluators           | Alternative | ET glasses  | Fixation points | Visual attention | Assumed         |                     |              |                                | Duration and number of fixations and their distances | Interpretability of visual behavior | Observed |                |                             |                 |                                    |                                    |
| Mussgnug *et al.* (2015)| Designers            | Additional data | ET glasses | Fixation points | Visual attention | Assumed         |                     |              |                                | Duration and number of fixations and their distances | Interpretability of visual behavior | Observed |                |                             |                 |                                    |                                    |
| Mussgnug *et al.* (2017)| Evaluators           | Alternative | ET glasses  | Eye–hand coordination | Ease of use | Assumed         |                     |                         |                                |                                   |                                   |                                |                 |                             |                 |                                    |                                    |
| Nagai *et al.* (2017)   | Evaluators           | Exploration of links | Remote ET | Analysis of gaze plot and heat map hotspot | Likelihood of purchasing a product | Observed         |                     |              |                                |                                   |                                   |                                |                 |                             |                 |                                    |                                    |
| Nguyen and Zeng (2010)  | Designers            | Alternative | EEG         | Beta power in channels FP1 and FP2 | Presence of an evaluation task (vs. the formulation of a solution to a design problem) | Observed         |                     |              |                                |                                   |                                   |                                |                 |                             |                 |                                    |                                    |
|                        |                      |             |             | Theta power in channel Fz | Observed         |                     |              |              |                                | Observed |                                   |                                |                 |                             |                 |                                    |                                    |
|                        |                      |             |             | Alpha power in channel Oz | Observed         |                     |              |              |                                | Observed |                                   |                                |                 |                             |                 |                                    |                                    |
| Nguyen and Zeng (2014a)| Designers            | Alternative | EEG         | Theta and Beta power in channel Fz | Creativity (of designers' thinking) | Not Proven       |                     |              |                                | Observed |                                   |                                |                 |                             |                 |                                    |                                    |
|                        |                      |             |             | Theta power in channel Fz | Conceptual clarity | X | Observed |                     |              |                                |                                   |                                   |                                |                 |                             |                 |                                    |                                    |
|                        |                      |             |             | Beta power in channel Fz | Effort | Observed |                     |              |                                |                                   |                                   |                                |                 |                             |                 |                                    |                                    |
|                        |                      |             |             | High-Beta power in channel Fz | Creativity (in a design task) | Observed |                     |              |                                |                                   |                                   |                                |                 |                             |                 |                                    |                                    |
| Nguyen and Zeng (2014b)| Designers            | Alternative | EEG         | Theta and Beta power in every channels | Mental effort | Assumed         |                     |              |                                | Observed |                                   |                                |                 |                             |                 |                                    |                                    |
|                        |                      |             |             | Alpha power in every channels | Observed |                     |              |              |                                | Observed |                                   |                                |                 |                             |                 |                                    |                                    |
|                        |                      |             |             | HRV | LF/HF | See Nguyen *et al.* (2013) | Mental stress | Assumed |                     | Observed |                                   |                                |                 |                             |                 |                                    |                                    |
|                        |                      |             |             | Number of segments at each stress level | Overall time under high stress | X | Observed |                     |              |                                |                                   |                                   |                                |                 |                             |                 |                                    |                                    |
|                        |                      |             |             | Time spent at each stress level | X | Observed |                     |              |                                |                                   |                                   |                                |                 |                             |                 |                                    |                                    |
| Source of the experiment | Role of participants | Kind of experiment | Biometric Tool | Corresponding measure or analysis method | Definition or relevant indications (excerpt from the source) | Connected variables or interpreted phenomenon | Inverse Relationship | Nature of the relationship |
|--------------------------|----------------------|--------------------|----------------|------------------------------------------|-------------------------------------------------------------|-------------------------------------------------|------------------------|--------------------------|
| Nguyen and Zeng (2017)   | Designers            | Exploration of links | EEG            | Beta2 power in channel Fz               | Mental effort                                                |                     | Proven (for 3 out of 6 tasks) |
|                          |                      |                    | GSR            | Normalized SCR                          |                                                              |                     | Assumed                      |
|                          |                      |                    |                | \(SC_{normalized} = (SC - Sc_{min})/(Sc_{max} - Sc_{min})\) |                                                              |                     |                             |
| Nguyen et al. (2013)     | Designers            | Alternative        | HRV            | LF/HF                                    | Mental stress                                                |                     | Proven                      |
|                          |                      |                    |                | The HRV frequency components are divided into Ultra Low Frequency (ULF) from 0 to 0.003 Hz, Very Low Frequency (VLF) band from 0.003 to 0.04 Hz, Low Frequency (LF) band from 0.04 to 0.15 Hz, and High Frequency (HF) band from 0.15 to 0.4 Hz (Camm et al., 1996) |
| Nguyen et al. (2015)     | Designers            | Confirmation of hypotheses | EEG            | Transient microstate percentage         | A microstate is a sub-second quasi-stable configuration of the scalp field map potential values that quickly changes to another quasi-stable configuration, Calculated through the P2ML algorithm | Hardness (of design problems) | Proven                      |
|                          |                      |                    |                |                                          |                                                              |                     |                             |
|                          |                      |                    |                | See Nguyen et al. (2015) Mental effort   |                                                              |                     | Assumed                      |
|                          |                      |                    |                | Alpha power in channel FP1              | Interpretability of the kind of fatigue (Type 1)            |                     | Assumed                      |
|                          |                      |                    |                | (Theta + Alpha)/beta power in channel FP1| Interpretability of the kind of fatigue (Type 2)            |                     | Assumed                      |
|                          |                      |                    |                | Alpha/Beta power in channel FP1         | Interpretability of the kind of fatigue (Type 3)            |                     | Assumed                      |
|                          |                      |                    |                | (Theta + alpha)/(alpha + beta) power in channel FP1| Interpretability of the kind of fatigue (Type 4)            |                     | Assumed                      |
|                          |                      |                    |                | (Theta/beta) power in channel FP1       | Interpretability of the kind of fatigue (Type 5)            |                     | Assumed                      |
|                          |                      |                    |                | Beta power in channel FP1               | Concentration                                                |                     | Assumed                      |
| Nguyen et al. (2019)     | Designers            | Alternative        | EEG            | Transient microstate algorithm          | Interpretability of designers' activities (as in design protocols) | Proven              |                             |
|                          |                      |                    |                | See Nguyen et al. (2015)                |                                                              |                     |                             |
|                          |                      |                    |                | PSD-based algorithm                     |                                                              |                     |                             |
|                          |                      |                    |                | PSD-based algorithm                     |                                                              |                     |                             |
| Park et al. (2012)       | Evaluators           | Alternative        | Dwell time     |                                          | Visual attention                                             |                    | Assumed                      |
| Remote ET | Total duration of fixations | Assumed |
|----------------|--------------------------------|---------|
| Total duration and distance of inter-fixation | Inter-fixation duration is the time between the end of a previous fixation and the start of the next | Visual exploration |
| Assumed |

Petkar et al. (2009) Designers Exploration of links Remote ET Average Pupil diameter and standard deviation Cognitive activity Observed

| Blinking frequency | Blinking frequency or blinking rate is the number of times the subject blinks in a minute | Difficulty and visual demand (of a task) | X | Observed |
|-------------------|-----------------------------------------------------------------------------------|------------------------------------------|----|---------|
| Blinking duration | Blink duration is the time interval between the time of blink initiation and the time at which the lowest point is reached by the eyelid during a blink | Cognitive workload | Observed |
| PERCLOS | Percentage of time spent while drooping with respect to a fixed time window of 120 s | Relax | Observed |
| Inter-blink interval | Time interval between two blinks | Demand (of a task) | Observed |

EEG Theta power in channel Fz Mental fatigue X Observed

| Alpha power in channel Oz | Task difficulty | Observed |
|---------------------------|-----------------|---------|
| Beta power in channels Cz, Pz, and Oz | | Observed |

Rojas et al. (2015a) Evaluators Additional data Remote ET Time to first fixation Amount of time (…) it took for the first fixation to occur in a given AOI, starting when the stimulus is viewed Visual attention X Assumed

| Total duration of fixations | Total fixation duration is the total duration (…) of all fixations within a given AOI | Assumed |
|-----------------------------|---------------------------------------------------------------------------------|---------|

Rojas et al. (2015b) Evaluators Alternative Remote ET Heat map hotspot (absolute duration, count, and relative duration) The absolute duration plot shows how long a subject has looked at different areas in the image. The count plot illustrates the accumulated number of fixations of all selected subjects. The relative duration plot shows the sum of the individual fixation lengths relative to the total fixation time on the image for each recording Attention (captured by visual elements) Assumed
| Source of the experiment | Role of participants | Kind of experiment | Biometric Tool | Corresponding measure or analysis method | Definition or relevant indications (except from the source) | Connected variables or interpreted phenomenon | Inverse Relationship | Nature of the relationship |
|--------------------------|----------------------|--------------------|----------------|------------------------------------------|------------------------------------------------------------|-----------------------------------------------|---------------------|--------------------------|
| Ruckpaul et al. (2014)   | Designers            | Alternative        | Remote ET      | Duration and frequency of fixations      | Presence of Concurrent Think-Aloud                         | X Observed                                    |                     | Observed                 |
|                          |                      |                    |                |                                         |                                                            |                                               |                     |                          |
| Ruckpaul et al. (2015)   | Designers            | Alternative        | Remote ET      | Mean duration of fixations               | Presence of interpretation phases                          | Proven                                        |                     |                          |
|                          |                      |                    |                |                                         |                                                            |                                               |                     |                          |
| Schmitt et al. (2014)    | Evaluators           | Exploration of links | Remote ET      | Percentage of dwell time                 | Relevance (of attributes)                                  | Assumed                                       |                     |                          |
|                          |                      |                    |                |                                         |                                                            |                                               |                     |                          |
|                          |                      |                    | EMG            | Normalized EMG value                     | Emotional arousal                                           | Assumed                                       |                     |                          |
|                          |                      |                    | GSR            | Normalized GSR values                    | Emotional arousal                                           | Assumed                                       |                     |                          |
| Seshadri et al. (2016)   | Evaluators           | Alternative        | Remote ET      | Percentage total duration of fixations   | Expectation to find relevant information                   | Assumed                                       |                     |                          |
|                          |                      |                    |                |                                         |                                                            |                                               |                     |                          |
| She and MacDonald (2018) | Evaluators           | Additional data    | Remote ET      | Percentage total duration of fixations   | Attention (paid to a specific attributes)                  | Assumed                                       |                     |                          |
|                          |                      |                    |                |                                         |                                                            |                                               |                     |                          |
| Shealy et al. (2017)     | Designers            | Additional data    | fNIRS          | Activation of the Left hemisphere        | Experience                                                  | X Observed                                    |                     | Observed                 |
|                          |                      |                    |                | Activation of the Right hemisphere       |                                                            |                                               |                     |                          |
| Study                  | Role       | Method          | Measure Description                                                                 | Interpretation                                                                 |
|-----------------------|------------|-----------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Shealy et al. (2018)  | Designers  | Alternative     | fNIRS                                                                                | Network density is the actual number of connections divided by the total number of possible connections |
|                       |            |                 | Observed                                                                             | Observed                                                                        |
|                       |            |                 | Activation of the Brodmann Areas: 6, 11                                              | Activation of the Brodmann Areas: 9, 46                                           |
|                       |            |                 | Interpretability of used design methods                                              |                                                                                |
| Steinert and Jablokow (2013) | Designers | Alternative     | EEG                                                                                  | Predictability of the shift between convergent and divergent design activities |
|                       |            |                 | Observed                                                                             | Proven                                                                          |
| Sun et al. (2013)     | Designers  | Additional data | EEG                                                                                  | Predictability of choice behavior                                                |
|                       |            |                 | Observed                                                                             | Proven                                                                          |
| Suzianti et al. (2015)| Evaluators | Additional data | FMRI                                                                                 | Predictability of choice behavior                                                |
|                       |            |                 | Observed                                                                             | Proven                                                                          |
| Sylcott et al. (2013) | Evaluators | Additional data | fMRI                                                                                 | Predictability of the shift between convergent and divergent design activities |
|                       |            |                 | Observed                                                                             | Proven                                                                          |
| Telpaz et al. (2015)  | Evaluators | Exploration of links | EEG                                                                                  | Predictability of choice behavior                                                |
|                       |            |                 | Observed                                                                             | Proven                                                                          |
| Ueda (2014)           | Evaluators | Exploration of links | EEG                                                                                  | Preference                                                                       |
|                       |            |                 | Observed                                                                             |                                                                                 |

(Continued)
participants interact with computer screens or the physical space, respectively.

- Neuroimaging instruments for the measurement of brain function and activation, such as electroencephalography (EEG) headsets and helmets, functional Magnetic Resonance Imaging (MRI) scanners, and functional Near-Infrared Spectroscopy (fNIRS) sensors and systems.

- Other instruments and sensors that capture biofeedback from the human body include the measure of Galvanic Skin Response (GSR), Heart Rate Variability (HRV), which is traditionally assessed by means of Electrocardiography (ECG), and muscles’ contraction by means of Electromyography (EMG).

The present paper takes for granted the functioning of the mentioned devices, the measures that are extracted, the events that are detected, for example fixations and saccades for ET, and the phenomena that are commonly inferred, e.g. arousal as a result of the sudden increase of people’s sweat captured by GSR meters. Such information can be independently extracted by contributions discussed in the paper, such as Liu et al. (2014), Hill and Bohil (2016), Lohmeyer and Meboldt (2016), Balters and Steinert (2017), Ergan et al. (2019), and Nguyen et al. (2019). Anyway, the measures that are benefited from in each source and the variables and phenomena that are associated to them are also included in Table 1 (fifth to ninth column), but such aspects will be discussed after the illustration of the reviewed contributions.

A further classification, still present in Table 1 (third column), will be used to organize the contributions in the next two sections. This classification concerns the way extracted biometric measures have been exploited for the scope of the experiments. As already clarified, biometric measures are behavioral variables used to describe a certain phenomenon. In general, such a phenomenon can also be explored by means of traditional methods, which leverage subjective reports very diffusely. The relationship between dependent variables obtained through biometric devices and traditional methods is the criterion that was used by the authors to classify the experiments. In addition, many contributions leverage independent variables included in the design of the experiment (usually referred as stimuli), that are manipulated in order to observe different effects and people’s behaviors, but these are not considered for the classification. The four classes in the numbered list below are ordered according to the expectedly growing maturity attributed to the use of biometric devices and to the corresponding capability of interpreting the extracted measures. In the first two classes, a relationship between traditional and biometric measures is found. However, the two reflect the difference between exploratory and confirmatory research, e.g. de Groot (2014), as two different steps included in empirical research to generate knowledge and formulate theories. Once this new knowledge has been gained, the phenomena of interest can be investigated reliably with biometric instruments, whose measures can be considered as empirically validated. Therefore, new integrated cycles of empiricism, as termed by Cash et al. (2016), can start. Accordingly, biometric measures disentangle from traditional measures in the last two classes. In class 3, the former and latter are meant to explore different nuances of the studied phenomenon. In class 4, the latter are absent and the studies rely solely on the former, likely thanks to previously generated knowledge inside or outside the design domain, for instance by the reverse inference process (Hutzler, 2014), where...
a consensus on the relation between physiological measures and cognitive variables has been found.

1) Exploration of links. These experiments are fundamentally exploratory studies in which the existence of correlations between biometric and traditionally extracted variables is investigated. Therefore, the potential and usability of biometric measures for specific scopes of design research is scrutinized by e.g. identifying the (combination of) measures that best describe a phenomenon, which has been contextually analyzed also with traditional methodologies requiring subjective assessments.

2) Confirmation of hypotheses. Based on previous findings (from design or other scientific domains) and/or logical deductions, some hypotheses are formulated that link, among others, biometric and traditionally extracted variables. Thus, these experiments verify whether biometric measures are capable of describing a given phenomenon in an expected way and, in positive cases, the verification of the hypotheses support their usability for extracting design-related information in a reliable way.

3) Additional data. In these experiments, the description of the studied phenomenon benefits from both biometric and traditionally extracted variables, whose relationship is not investigated or questioned. The validity of the former is, therefore, taken for granted along with the way to interpret biometric measures in the specific design context. Anyway, here, biometric measures are not considered appropriate for a full-spectrum investigation of the analyzed phenomena.

4) Alternative. These experiments do not include traditionally extracted variables. In some cases, the analyzed phenomena are studied for the first time with biometric devices, which represent an enabling technology for the treated research areas. In other cases, traditionally extracted measures taken in the past in the same domain are considered unreliable and substituted by biometric ones. Diffusedly, the variation of biometric variables is observed as a result of the manipulation of stimuli. In all these circumstances, the validity of biometric measures is not questioned, and their interpretation considered sufficiently straightforward to use them as a substitute of participants’ conscious answers. This consideration allows for reckoning this class of experiments the one featured by the highest maturity attributed to biometric measures.

In light of the above definitions, the classification of the surveyed experiments follows the rationale underpinned by the flowchart depicted in Figure 1. As some experiments included more analyses and could refer to more than one class, the authors included these contributions in the category ascribable to the main objectives and findings of the corresponding manuscripts.

Additional characterizations of the experiments will be introduced in the followings: as this additional classification slightly differs for product evaluation and designer-related contributions, it will be presented in the next two corresponding sections.

**Design evaluations using biometric devices**

The contributions that are described in detail in the present section include studies that, to different extents, inform designers about the desirable characteristics of products and how representation and supplementary information affects human perception.
Beyond the “kind of experiment” achievable from Table 1, the authors have characterized these contributions further (see Tables 2–5) in order to point out peculiarities that might well imply the complexity, the outreach, and the reliability of the contributions. The “additional dimensions” (as they will be indicated hereinafter) for a more comprehensive characterization of the contributions are listed below.

### Table 2. Characterization of experiments concerning products evaluation and addressing the search for a link between biometric data and variables extracted with traditional methods

| Source                  | Field                                  | Number of Participants | Stimuli                          | Illustration  | Different elicitation methods | Data Analysis                          |
|-------------------------|----------------------------------------|------------------------|----------------------------------|----------------|--------------------------------|----------------------------------------|
| Carbon *et al.* (2006)  | Automotive                             | 16                     | Drawings and Sketches            | Sequence       | Questionnaire                 | ANOVA                                  |
| Dogan *et al.* (2018)   | Engineering Design                     | 24                     | Virtual Prototypes               | Sequence       | Questionnaire                 | Regression Analysis, Neural Networks    |
| Guo *et al.* (2016)     | Consumer Goods                         | 26                     | Photorealistic Pictures or Photos| Sequence       | Questionnaire                 | ANOVA                                  |
| Guo *et al.* (2019)     | Consumer Goods                         | 29                     | Virtual Prototypes               | Sequence       | Questionnaire                 | ANOVA                                  |
| Ho and Lu (2014)        | Engineering Design, Consumer Goods     | 32                     | Photorealistic Pictures or Photos| Sequence       | Questionnaire                 | ANOVA                                  |
| Hsu *et al.* (2017)     | Consumer Goods                         | 20                     | Drawings and Sketches            | Sequence       | Questionnaire                 | PCA, ANOVA                             |
| Khushaba *et al.* (2013) | Consumer Goods                         | 18                     | Virtual Prototypes               | Sequence       | Preference Indication         | ANOVA                                  |
| Kim *et al.* (2016)     | Engineering Design, Consumer Goods     | 12                     | Drawings and Sketches            | Sequence       | Questionnaire                 | PCA                                    |
| Köhler *et al.* (2015)  | Consumer Goods                         |                        | Photorealistic Pictures or Photos| Sequence       | Questionnaire, Preference Indication | ANOVA                                  |
| Kukkonen (2005)         | Consumer Goods                         | 28                     | Photorealistic Pictures or Photos| Groups         | Questionnaire, Preference Indication | Correlations                           |
| Laohakangvalvit and Ohkura (2017) | Consumer Goods, Graphics and Fashion Design | 40                     | Drawings and Sketches            | Sequence       | Questionnaire, Preference Indication | Descriptive statistics               |
| Li *et al.* (2018)      |                                       | 14                     | Photorealistic Pictures or Photos| Sequence       | Questionnaire, Preference Indication | Correlations, Neural Networks          |
| Lou *et al.* (2017)     | Engineering Design, Architecture and Civil Engineering | 14                     | Photorealistic Pictures or Photos, Virtual Prototypes | Sequence | Questionnaire | Descriptive statistics |
| Nagai *et al.* (2017)   | Packaging Design                       | 30                     | Photorealistic Pictures or Photos| All together   | Questionnaire, Interview, Preference Indication | ANOVA                                  |
| Schmitt *et al.* (2014) | Automotive                             | 14                     | Photorealistic Pictures or Photos| Sequence       | Questionnaire                 | ANOVA, Statistical tests               |
| Telpaz *et al.* (2015)  | Consumer Goods                         | 15                     | Photorealistic Pictures or Photos| Sequence, groups | Questionnaire, Preference Indication | Regression Analysis                |
| Ueda (2014)             | Consumer Goods                         | 10                     | Photorealistic Pictures or Photos| Sequence       | Questionnaire, Preference Indication | ANOVA                                  |
| Wang *et al.* (2010)    | Automotive                             | 50                     | Photorealistic Pictures or Photos| Sequence       | Preference Indication         | ANOVA                                  |
| Yang *et al.* (2017)    | Consumer Goods                         | 20                     | Photorealistic Pictures or Photos| Sequence       | Questionnaire                 | ANOVA                                  |
| Yilmaz *et al.* (2014)  | Graphics and Fashion Design            | 15                     | Photorealistic Pictures or Photos| Sequence       | Preference Indication         | ANOVA, Statistical tests               |
Table 3. Characterization of experiments concerning products evaluation in which hypotheses are formulated as for the relationship between biometric data and variables extracted with traditional methods

| Source                          | Field                | Number of Participants | Stimuli                                          | Illustration | Different elicitation methods | Data Analysis                  |
|---------------------------------|----------------------|------------------------|--------------------------------------------------|--------------|-------------------------------|--------------------------------|
| Aurup and Akgunduz (2012)       | Automotive           | 14                     | Photorealistic Pictures or Photos                | Groups       | Preference Indication, Interview | Regression Analysis            |
| Boa et al. (2015)               | Consumer Goods       | 17                     | Drawings or Sketches                             | Groups       | Questionnaire                 | ANOVA                          |
| Burlamaqui and Dong (2017)      | Consumer Goods       | 61                     | Photorealistic Pictures or Photos                | Sequence     | Questionnaire                 | Regression Analysis            |
| Du and MacDonald (2014)         | Automotive           | 72                     | Photorealistic Pictures or Photos                | Sequence, Groups | Questionnaire | Descriptive statistics, ANOVA, Regression Analysis |

Table 4. Characterization of experiments concerning products evaluation in which biometric data and variables extracted with traditional methods are extracted to provide a comprehensive description of the studied phenomenon

| Source                          | Field                              | Number of Participants | Stimuli                                          | Illustration | Different elicitation methods | Data Analysis                  |
|---------------------------------|------------------------------------|------------------------|--------------------------------------------------|--------------|-------------------------------|--------------------------------|
| Boa et al. (2013)               | Consumer Goods                     | 20                     | Photorealistic Pictures or Photos, Drawings or Sketches | Sequence     | Questionnaire                 | ANOVA                          |
| Borgianni et al. (2019)         | Consumer Goods                     | 43                     | Physical Products                                | Sequence     | Questionnaire                 | PCA, Regression Analysis       |
| Du and MacDonald (2015)         | Automotive                         | 36                     | Photorealistic Pictures or Photos, Text          | Sequence, Groups | Questionnaire, Preference Indication | Statistical tests             |
| Du and MacDonald (2018)         | Consumer Goods                     | 79                     | Virtual Prototypes                               | Sequence     | Questionnaire                 | ANOVA, Statistical tests       |
| Ergan et al. (2019)             | Architecture and Civil Engineering | 40                     | Virtual Prototypes                               | Sequence     | Questionnaire                 | Descriptive statistics, Statistical tests |
| He et al. (2017)                | Engineering Design                 | 40                     | Drawings or Sketches, Text                       | Sequence     | Questionnaire                 | Descriptive statistics         |
| Hurley et al. (2013)            | Packaging Design                   | 127                    | Physical Product                                 | All together | Preference Indication         | ANOVA, Statistical tests       |
| Ishak et al. (2015)             | Consumer Goods                     | 8                      | Photorealistic Pictures or Photos                | All together | Preference Indication, Think-Aloud Method | Descriptive statistics         |
| Maccioni et al. (2019)          | Consumer Goods, Packaging Design, Automotive | 43           | Photorealistic Pictures or Photos                | Sequence     | Questionnaire                 | PCA, Regression Analysis       |
| Rojas et al. (2015a)            | Packaging Design                   | 38                     | Photorealistic Pictures or Photos, Virtual Prototypes | Sequence, Groups | Questionnaire | Descriptive statistics, Statistical tests |
| She and MacDonald (2018)        | Consumer Goods                     | 38                     | Photorealistic Pictures or Photos, Text          | Sequence     | Questionnaire, Interview      | ANOVA                          |
| Suzianti et al. (2015)          | Packaging Design                   | 30                     | Virtual Prototypes                               | All together | Questionnaire, Think-Aloud Method | ANOVA, Descriptive statistics |
| Sylcott et al. (2013)           | Engineering Design, Automotive     | 28                     | Drawings or Sketches, Text                       | Groups       | Preference Indication         | Regression Analysis, Statistical tests |
Table 5. Characterization of experiments concerning products evaluation in which biometric data are used, and the outputs of subjective assessments are absent or neglected

| Source                  | Field                                  | Number of Participants | Stimuli                              | Illustration | Different elicitation methods | Data Analysis               |
|-------------------------|----------------------------------------|------------------------|--------------------------------------|--------------|------------------------------|-----------------------------|
| Hyun et al. (2017)      | Automotive                             | 10                     | Drawings or Sketches                 | Sequence     | Questionnaire                | Regression Analysis         |
| Khalighy et al. (2015)  | Consumer Goods                         | 50                     | Drawings or Sketches                 | Groups       | Questionnaire, Preference Indication | Regression Analysis         |
| Kovačević et al. (2018) | Packaging Design                       | 24                     | Photorealistic Pictures or Photos    | Sequence     |                              | Descriptive statistics, ANOVA |
| Koivunen et al. (2004)  | Consumer Goods                         | 20                     | Photorealistic Pictures or Photos    | Sequence     |                              | Statistical tests           |
| Li et al. (2017)        | Consumer Goods, Graphic and Fashion Design | 15                   | Photorealistic Pictures or Photos    | Sequence     |                              | Descriptive statistics      |
| Mussgnug et al. (2014)  |                                       |                         | Physical Products                   | Single       |                              | Statistical tests           |
| Mussgnug et al. (2017)  | Engineering Design                     | 40                     | Physical Products                   | Single       |                              | Descriptive statistics      |
| Park et al. (2012)      | Graphic and Fashion Design             | 43                     | Photorealistic Pictures or Photos    | Sequence     | Questionnaire                | ANOVA, Descriptive statistics, Statistical tests |
| Rojas et al. (2015b)    | Packaging Design                       | 28                     | Photorealistic Pictures or Photos    | Sequence     | Questionnaire                | Descriptive statistics      |
| Seshadri et al. (2016)  | Automotive                             | 19                     | Photorealistic Pictures or Photos    | Sequence, Groups | Questionnaire                | ANOVA                      |
| Yang et al. (2016)      | Consumer Goods                         |                         | Physical Products, Photorealistic Pictures or Photos |                       | Statistical tests               |

• **Field.** It clarifies the design field that is focused on in the experiment, when clarified or inferable from the typologies of illustrated products. The standard categories are Engineering Design, Architecture and Civil Engineering, Packaging Design, Graphics and Fashion Design, Consumer Goods, and Automotive. Although the latter could be included in other classes, it has been separated due to the numerous examples available.

• **Number of participants.** Undoubtedly, the number of subjects involved in the experiment is a proxy of relevance and reliability, as suggested by Robinson (2016), among others.

• **Stimuli.** It stands for the form of presentation of the products, which can clearly affect the experimental results. The standard classes are Physical Products, Photorealistic Pictures or Photos, Text, Virtual Prototypes (including CAD representations), and Drawings and Sketches.

• **Illustration.** It addresses the logic used for showing the sample of products manipulated in the experiment. The standard categories are Single (just a product is shown in the whole experiment), All together (all the products of the sample at the same time), sequence (a series of one product each), and Groups (a sequence in which each step includes more than one product).

• **Different elicitation methods.** It concerns the traditional methodologies or processes employed for extracting dependent variables, which, in most cases, elicit the conscious answers provided by participants. The standard categories are Questionnaire (multiple questions are present), Preference Indication or choice (actually a much diffused subclass of the former, worth considering independently), Interview, and Think-Aloud method.

• **Data Analysis.** It indicates the family of statistical techniques used to corroborate the findings. Actually, statistical methods are not used in all the studies, and some of them are qualitative only. In other cases, these are not explicated. The level of sophistication and reliability of employed statistical techniques is plainly a metric of the impact of results (Bettis et al., 2016; Robinson, 2016). The standard categories are Descriptive statistics (e.g., calculations of average values and standard deviations, distributions of data), Correlations, Statistical tests, PCA (Principal Component Analysis), Regression Analysis, ANOVA (Analysis of Variance and the whole family of methods that focus on variability and covariance of data), Neural Networks, and Fuzzy Sets.

Experiments classified as “Exploration of links”

The main objectives of the studies presented in this subsection are specifically ascribable to user experience, emotions, and the effects of different product features and representations, including preferences. Therefore, affective design and emotional engineering and the previous knowledge of products are particularly addressed by the presented contributions, whose characterization in terms of additional dimensions is to be found in Table 1.
**Attractiveness and preferences**

Within the whole set of explorative studies, a seminal work in the design domain can be considered the one described in Carbon et al. (2006). Here, with particular reference to the automotive industry, remote ET is used to study the capability of rated design innovativeness to predict attractiveness and the effects of complexity. In particular, the results show significant differences in the way fixations take place in highly innovative designs, characterized by a balanced exploration of the different areas of the pictures. Innovative features within the shown pictures have a high probability of receiving the first fixation, while complexity presents a significant correlation with pupil dilations. Attractiveness is also a core topic in Laohakangvalit and Ohkura (2017), which links ET data to kawaiiiness, a far-East concept standing for cuteness and charm. The findings show that objects (spoons in this specific case) featured by higher attractiveness rates tend to display larger numbers of fixations with particular reference to those Areas of Interest (AOIs) critical for evaluations and preference formation. The research presented by Li et al. (2018) specifically focuses on appearance. The evaluation of this dimension on a number of aircraft seats is correlated with a variety of ET measures. A best-fit mathematical model linking subjective and biometric measures is then created with the support of Neural Networks, that is a computer-supported method that simulates neural responses. Guo et al. (2019), who base their study on a series of desk lamps, find links between aesthetic evaluations and measures taken with ET and EEG. The former enable the definition of three sets of lamps grouped according to visual aesthetic levels, which are then compared in terms of the latter. Fixation time ratios, dwell times, and alpha power have a significant direct relationship with high levels of visual aesthetics, while an inverse relationship characterizes gamma power. By using the extracted biometric data, some machine learning classifiers outperform the accuracy of previous studies on products’ aesthetics.

The interpretation and possible prediction of preferences is the thrust of several other contributions. In Kukkonen (2005), the number of fixations on individual products emerges as a good predictor for the indication of the preferred mobile telephone, although the same variable failed to explain the rank among different variants. The experiment presented in Nagai et al. (2017) includes ET, questionnaires, and interviews on preferences. It captures the relevance of factors for a buying decision on tea bottles, which are represented in a fashion similar to a supermarket shelf. Through the support of heat maps based on the total length of fixations, the results show that, beyond quality factors, the product display is a very influencing parameter when consumers purchase products.

The use of EEG is also common for studies on product preferences and choice decisions. Some EEG data are found to have high explanatory power for preferences, namely the neural activity measured by a mid-frontal electrode when participants are preliminarily exposed to pictures of products (Telpaz et al., 2015). Similarly, Wang et al. (2010) observe a significant increase in the EEG power at the alpha and beta frequencies when the participants are looking at the favorite car model among a proposed set. Still with a focus on the frequency of EEG signals, Yilmaz et al. (2014) individuate those channels that can be regarded as the most discriminative for like/dislike decisions and consequent elicitation of preferences. Specifically, these include a frontal channel on the left and a temporal channel on the right for low frequencies, as well as a central channel and an occipital channel on the left for high frequencies. With a similar research approach benefitting from the use of EEG, Ueda (2014) finds increased neural activity in the gamma frequency in the temporal and the prefrontal regions during the illustration of products participants expressed preference for. Khushaba et al. (2013) highlight a significant modification in the EEG power in the frontal, temporal, and occipital regions during participants’ indication of preferences. The study clarifies which frequency bands and electrodes are mostly involved. Interestingly, this experiment uses a remote ET, which, rather than benefitting the study with additional measures, is intended to discriminate what participants were looking at, so that just relevant time intervals are analyzed with the EEG system. Additionally, the design of the experiment includes controlled variations of the products shown (crackers), and the effects of feature changes are assessed with reference to both preference indications and EEG data.

**Semantic description and attributes**

Product features, attributes, and (semantic) descriptions are focused on in several studies. Adjective-based design is supported by the results provided by Dogan et al. (2018), who use vessel hulls in their case study to infer which parts of the product are critical to the designation of specific adjectives. Variations of geometries and characteristics are proposed to participants, who attribute adjectives to each representation. All the presented models are subdivided into AOIs standing for different components, which enables the identification of parts of the hull and the corresponding design parameters to be attributable to the selected adjectives. Lou et al. (2017) focus on the classification of customer requirements by means of Kano’s quality attributes (Kano et al., 1984) as a means to support conceptual design. These are supposed to give rise to different physio-psychological reactions, which can be, therefore, extrapolated through EEG. After the experiment, a best-fit formula is found that links quality attributes designated with the classical procedure (the Kano evaluation table) with a variety of EEG signals. ET is used in Köhler et al. (2015) to identify and rank the AOIs (corresponding to products’ components) featured by major observation times, so that they can be linked with overall preferences and intended adherence to product’s semantic descriptions. The study elucidates which parts of the studied products (watches in this case) are the most influential in the determination of their appropriateness for a semantic description, thus extending the common outreach of Kansei Engineering (Nagamachi, 1995) experiments. Like in other studies, ET also supports the identification of the features deemed as the most critical for the formation of overall preferences.

**Emotions**

Kansei Engineering is dealt with also in Hsu et al. (2017). More products are presented as stimuli, observed through a remote ET and characterized with the circumplex model of affect (Russell, 1980) articulated on pleasure/arousal and frequently adopted in Kansei Engineering. Variables emerging from the ET are then analyzed to find a relationship with both pleasure and arousal in order to build an alternative method for classification. Among the results, the contribution stresses the link between high levels of pleasure and participants’ visual attention, while low levels are characterized by an increased number of fixation points. As aforementioned, emotions are widely studied in the contributions grouped in this subsection, and this takes place beyond paying attention to Kansei Engineering. A sequence of images in the fashion of sketches is the base for the experiment presented in
Kim et al. (2016). Conscious evaluations of the sketches include the self-assessment manikin (Hodes et al., 1985), that is an approach to elicit emotions’ arousal and valence, the evaluation of images’ matching with emotional and semantic terms by means of a Likert scale and a final ranking. The use of a GSR meter during the experiments enables correlations with biometric data, which supports the usability of this device as a substitute for arousal measures. Schmitt et al.’s (2014) goal is to infer rules for emotional product design. Their experiment gathers conscious evaluations about depicted product variants, featured by different components, and corresponding semantic concepts along with data extracted with GSR, EMG, and ET. While ET pursues the objective of individuating what participants look at in specific time intervals, the two biofeedback sensors are meant to recognize emotional states. The statistical analysis reveals the role played by proposed semantic concepts in shifting participants’ gaze toward different areas of product representations, which give rise to significant perturbations of GSR and EMG signals attributable to emotional responses. In Ho and Lu (2014), pictures presenting different products are displayed along with images taken from the International Affective Picture System (IAPS). The latter is leveraged as a standard control. The degree of emotions aroused by products is anyway monitored through subjective assessments too, which, by the way, largely confirmed valence and arousal of IAPS pictures. The whole experiment is supported by a remote ET system, and it reveals that pupil size is effective in identifying products that elicit negative emotions.

User experience
Within studies of user experience, two contributions can be mentioned that aim to assess the degree of user experience, deemed as a dimension of product knowledge and value. The products shown in Guo et al. (2016) are first freely observed by participants whose gaze is monitored through ET and then evaluated in terms of perceived experience with the products themselves. The outcomes of the experiment indicate that products marked by a higher degree of experience attract participants’ attention faster, and they are looked at longer. Conversely, less familiar products engender larger variations of the pupil diameter. Yang et al. (2017) measure product familiarity in different forms (EEG and questionnaires), which are then linked to the effectiveness and speed of recognition of objects shown in two different phases. Variants of consumer goods are shown in the two-stage experiment, which differ in terms of color, material, and shape (these parameters are taken into account too). The link between familiarity and recognition is found, while the pros and cons of the different measuring strategies (brain functions vs. questionnaire) are discussed.

Experiments classified as “Confirmation of hypotheses”
Du and MacDonald (2014) formulate eight hypotheses concerning the relationship between product features (rated importance and the effects of size change) and ET variables. Especially with reference to specific ET measures (fixation times and frequency), the results support the positive relationship with the perceived importance of corresponding product features. This is revealed when different product alternatives are shown simultaneously. In addition, the scholars find that the size of features affects fixations (the larger the size, the more and longer the fixations) and, consequently, attributed importance and preferences. Still, with a focus on product features and representation, Boa et al. (2015) investigate whether the similarity between product couples depends on engagement with product features, which is measured in terms of fixations on the corresponding AOIs. The study, considered as a preliminary attempt in the field of styling decisions, reveals a weak effect between feature engagement and the similarity ratings of product pairs. The experiment described in Aurup and Akgunduz (2012) is another example in which product pairs are shown and evaluated. Here, the employed neurophysiological tool is an EEG system, which makes it possible to test the relationship between preference and signal power in the alpha peak range, namely the 8–12 Hz band. Participants express their preference for products after having been shown standard images from the IAPS, used as a reference as in other papers. The EEG is used throughout the whole experiment. Besides demonstrating the hypothesized above relationship, the scholars individuate, through the EEG and within the studied band, different critical frequencies for right- and left-handed people.

The experiment reported in Burlamaqui and Dong (2017) is designed to test the relationship between intended affordances and gaze events also in light of the level of novelty or surprise aroused by products. Despite the formulated hypotheses are discarded, the findings are, however, relevant in the field of user-product interaction, as design elements to be stressed emerge when the design is intended to favor interpretation and usability. The results show that the identification of or the search for the intended affordance of a product leads people to gaze at locations where the function is supposed to take place instead of areas responsible for the interaction with the user (as initially hypothesized).

Table 3 summarizes the contributions included in this subsection and characterizes them in terms of the additional dimensions.

Experiments classified as “Additional data”
Product representation, such as features and attributes, is the main domain of application for the contributions included in this subsection too. In a number of papers, ET is used to help determine people’s reactions to different forms and modalities chosen to illustrate products or designs. He et al. (2017) test the browsing efficiency when parts of assemblies in mechanical drawings are marked by text or digits. By introducing ET in the experiment, the scholars find that the former way of marking drawings is more effective in terms of both enabling the quick individuation of critical parts and enhancing participants’ perceived satisfaction. In a very different context, the study presented by Hurley et al. (2013) deals with the role played by packaging on potential consumers’ appreciation for products. In particular, the experiment is concerned with the different degrees to which packaging is transparent or conceals the product that is contained. ET data support evidence offered by traditionally extracted variables in that they confirm preferences toward visible products. Covering packaging gives rise to significantly fewer fixations with a lower total duration. In Boa et al. (2013), ET is used to provide additional information related to the link between product representation variants (sketches, renders, and photos) and individuals’ preferences, perception and judgement. In the results, significant correlations of the form of representation are found with neither the gazing behavior nor the designation of preferences. The findings from Rojas et al. (2015a) are partially contradicting, as participants’ stated perception is affected by renders with medium quality (if
compared to photos), while the orientation of the examined products significantly impacts on ET variables. The thrust of the experiment illustrated in Suzianti et al. (2015) is to study the effect of text, fonts and variations thereof, and color of packaging on product preferences. As for ET results, longer fixations and visitations of areas, assumed to relate to preferences, show the non-negligible role of the examined factors. Text is also dealt with in some experiments conducted by MacDonald and colleagues; however, text is here studied from the content-related point of view and not as graphical characteristic. In Du and MacDonald (2015), product descriptions are administered to participants in three different representation forms, namely textual, pictorial, and a combination of the two. Thanks to ET data, it emerges that the model of cancellation-and-focus in comparison processes, namely similarities are initially individuated and quickly ignored, applies just to text-only representations. Non-shared features receive, on average, longer fixation times also when it comes to images, but contextual factors are relevant as well. Text-based sustainability triggers, i.e. descriptions concerning environmental performances, that integrate product pictures are in focus in She and MacDonald (2018). By means of ET, the experiment reveals that the presence of sustainability triggers significantly increases the number of fixations on sustainable product attributes, while the effect on the percentage of fixations is not significant. Other aspects of the studied phenomenon are analyzed in relation to answers to questionnaires and indication of preferences. The effects of products’ sustainability and their perceived value are also studied in Maccioni et al. (2019), who leverage questionnaires, a remote ET and a GSR meter, so as to include conscious and unconscious aspects in the evaluation process. In particular, biometric measures enrich the set of value dimensions attributed to products, which are displayed as pictures. All the measures are combined through a PCA and associated to the existence/lack of eco-design efforts that feature 40 products analyzed by 43 participants. This combination allows revealing that “greener” products give rise to particular interest in light of identifiable creative traits, which is even more remarkable in subjects with a greater sensitivity to environmental issues but can be penalized by conservative approaches that lead to prefer products whose performances are known and taken for granted.

Other contributions regard product features more closely. Tradeoffs between form and function, whose study is supported by fMRI, are the thrust of Sylcott et al. (2013). Participants are asked to make choices among product alternatives featuring the variation of form, function, or both. The experiment discloses similarities and differences in the brain networks involved by the mentioned forms of variations. In particular, brain regions linked to emotions are particularly activated when decisions are made in the presence of conflicts between form and function. Ishak et al.’s (2015) contribution complements previous studies on the relevance of culture-related product attributes; to this aim, a traditional Malaysian artifact is here evaluated. Participants in the experiment are people with large experience of said artifact. The use of the ET enables the determination of the parts of the object that are fixated first and for longer times and that are assumed as those mostly contributing to the perception of its effectiveness and usage efficacy. Du and MacDonald (2018) study the relationship between specific product features and the perception they provoke. In particular, they manipulate visual cues to change products’ geometries completely or for specific parts. The scholars investigate whether these modifications of morphologies affect the perception of products’ environmental friendliness, which, purposefully, is not actually measured. The experiment is structured in two parts: an association-building task, where users create their mental association between cues and perceived environmental friendliness, and a testing task. Thanks to a remote ET, the scholars demonstrate how, in the testing task, the participants fixate on critical cues for their evaluations longer than in the association-building task. This contributes to demonstrating the capability of cues and specific morphologies to subliminally change the perception of attributes that cannot be actually assessed by participants, such as environmental friendliness.

Features that are intentionally more visible than in previous cases and new technologies characterize two recent contributions. Borgianni et al. (2019) investigate the effect of substituting commercial products with 3D-printed replicas of mid-low quality. Original and 3D-printed objects are evaluated subjectively through a specific questionnaire by 43 participants, who wear ET glasses. Participants’ answers and ET measures are combined with a PCA, which, besides, reveals a weak relationship between the two sources of data. The experiment demonstrates that 3D-printed objects attract more curiosity; their level of attractiveness is unsurprisingly significantly lower than that of original products, but this is not proportional to the perceived gap in terms of fitness to scope. In a very different field, Ergan et al. (2019) use self-reports and multiple biometric measures (EEG, GSR, and HRV) to assess the effects of architectural design changes in built environments reconstructed with Virtual Reality technologies. Tested environments are characterized by the presence of supposedly relaxing and stressful characteristics. The former, according to results, give rise to enhanced oscillations in theta, alpha, and beta bands for many EEG channels, while the latter are featured by increased HRV.

The characterization of the presented contributions in terms of the additional dimensions is available in Table 4.

Experiments classified as “Alternative”

The contributions grouped in this subsection do not include elicitation of subjective assessments, or these are used to urge participants to carry out some tasks and are not considered in the subsequent analysis. In many cases, the effects of different stimuli on biometric measurements are studied to infer conclusions.

The contributions of the group are organized in the following paragraphs, featured by the topic of the investigation. The further characterization of the illustrated contributions by means of additional dimensions is found in Table 5.

Observation patterns and their relationship with aesthetic concepts

Koivunen et al. (2004) illustrate a seminal work in the context of product observation supported by ET. People’s observation patterns are indeed analyzed, and three different observation styles are inferred, namely narrow, holistic, and combined strategies. It is suggested that these strategies, to be confirmed with further research, should be taken into account in studies of product design and evaluation. Park et al. (2012) use ET to study the visual behavior of participants with different training levels – in general, fashion designers are considered more experienced in product visualization than other individuals are. The scope is to provide a major understanding about ways to train the aesthetic visualization, which, according to results, does not take place with the repetitive illustration of the same image. The outcomes also
show that more trained viewers tend to gaze longer and have a higher frequency of fixations over the presented products. As well, they demonstrate to be more sensitive to design changes, as revealed by the time required to scan the image. Still, in the field of fashion design, EEG and ET data are used as proxies for quantifying the evaluation factors related to product appearance (Li et al., 2017). Here, the authors address the need to take biometric measures due to the unreliability of subjective evaluations, in particular with respect to beauty. The concept of beauty is particularly focused on also in Khalighy et al. (2015). A two-stage experiment is conducted with a different sample of participants. First, based on the results of people’s exposition to images with known beauty, a new formula is devised that is capable of assessing beauty as a function of various ET measures, markedly number, duration, and coordinates of eye fixations. Then, the validity of the formula is validated with a test, in which participants express a preference to products while being monitored with ET.

**User experience and user-product interaction**

Some qualitative studies include the use of ET for studying user-product interaction. In Mussgnug et al. (2014), it is shown that mobile ET makes it possible to reveal previously hidden aspects of user experience. Design students learn to analyze ET outputs (videos in particular) to evaluate usability aspects and identify both explicit and implicit user needs. The study of user experience is enhanced in Mussgnug et al. (2017), where recordings of ET glasses, combined with the monitoring of hand gestures, are used to detect cognitively demanding actions and operations. To the scope, the scholars hypothesize that cognitive demanding handling interactions are represented by long periods of constant hand–gaze distance, as, in these phases, the hand and the gaze are involved in the same action. The combination of ET with the monitoring of hand movements is to be found in Yang et al. (2016) too. The work aims to provide a major understanding of user intent when interacting with products or representations thereof. To the scope, gaze data including fixations and visitations of AOIs are here interpreted as proxies of attraction, attention, and popularity.

**Product features and semantic priming**

In the experiment presented by Rojas et al. (2015b), participants are monitored with EEG and remote ET while they are exposed to adjectives (a set of positive and negative ones is proposed) and pictures of alternative packages for cold cuts. They are subsequently asked about the consistency of adjectives and pictures with a yes/no option. Data extracted from the EEG are elaborated, and the link between the obtained variables and adjectives is investigated. This reveals that the valence (positive vs. negative) of the semantic priming featured by adjectives is statistically correlated with some of these EEG variables (details are to be found in Table 1). ET data are instead focused on during the presentation of the pictures and are meant to study the change in observed AOIs based on the semantic priming. Seshadri et al. (2016) study how different tasks within the observation of car photos affect ET data. In particular, the numbers of fixations on different perspective representations of the cars (front, side, and rear) are investigated. The results show that different representations attract the most attention according to the tasks, which include, for the car models, general appreciation, identification of the brand, and evaluation of the correspondence to adjectives used as semantic primes. The paper authored by Hyun et al. (2017) uses the duration of fixations on AOIs to infer participants’ looking probability of design elements of 119 car models from 23 different brands. The scope is to link this data with the design similarity of car brands, which have been previously estimated based on typical and novel design elements. During the experiment, the car brand familiarity and brand’s design recognition are also assessed through questionnaires; these outputs are used as control variables. The results show correlations of looking probabilities of specific car elements ensuing from ET with both design similarities and the recognition of the brand. The contribution is, therefore, able to discern which design elements are the most relevant to recognize car brands and to characterize them according to their market segment. Eventually, a study on warnings displayed on packaging is presented in Kovačević et al. (2018). Here, a remote ET measures the time to first fixations on warnings as a metric of their noticeability, revealing significant effects brought about by increasing dimensions of the warnings.

**Studies of design processes and designers’ cognition with biometric devices**

Despite the shared use of biometric measures and the relevance of design, the contributions included in the present section largely differ from those focused on the evaluation of products. The shift of attention from products to design processes and cognition, which accompanies the shift from evaluators to designers, results in a change in conditions and methods that are focused on, and, diffusely, in approaches to conduct the studies. This is reflected in the additional dimensions considered relevant to the experiments described in the present section. Indeed, some of the additional dimensions to characterize the contributions found in the previous section are invalid, and a new list has been created. The unchanged dimensions and articulations thereof are Number of participants and Data Analysis. New or modified dimensions are added as in the followings.

- **Background of designers.** It indicates the specific group of designers that are involved in the experiment and if different levels of expertise are critical to the study. Designers are distinguished into Expert Designers, Novice Designers, Engineering Students, Graduate Students from Architecture schools, Graduate Students from Engineering schools. When relevant, other indications are included.
- **Task.** It indicates which specific tasks the designers have to perform during the experiment. They include ideation (which comprises open-ended and creative tasks), Problem-Solving (well-defined), Problem-Solving (ill-defined), Decision-making, Sketching or manually drawing, Observing (and evaluating) technical drawings, Using CAD (and/or other computer-aided systems relevant to design), Non design-related tasks (e.g., tests to infer designers’ cognition in certain circumstances).
- **Stimulated task.** It indicates (Yes/No) if the task to be performed is perturbed by stimuli or external interventions, at least for a subset of participants. This perturbation is often the focus of the study.
- **Different Elicitation Methods.** As aforementioned, this field also appears in product evaluation experiments, but the leveraged methods differ substantially here. The categories are Assessing task performances (normally carried out by external judges, for instance with respect to creativity metrics), Questionnaire, Interview (including more non-structured information
elicitation methods, such as reports), Video Analysis (also used as a support for segmenting design tasks), Think-Aloud Method.

The characterization of the papers based on these additional dimensions is to be found in Tables 6–9, still distinguished according to the kind of experiment.

**Experiments classified as “Exploration of links”**

Petkar et al. (2009) present a seminal and preliminary work to evaluate mental workload in designers by means of ET and EEG. The scholars benefit from an established psychological test, the Stroop test (Stroop, 1935), to set baseline levels of mental stress for each designer. The performances in the test and biometric data are then linked. The outcomes show (a) positive and strong correlations between performance and blinking frequency and duration; (b) an opening up (down) parabolic pattern that links the mean pupil diameter (blinking frequency) and the workload of the task; and (c) the signal power revealed by the EEG in the alpha, beta, and theta bands tends to increase for many brain regions with the difficulty of the tasks and their corresponding workload up to a saturation point. Mental stress is also studied in the two experiments that follow. In Nguyen and Zeng (2017), data from GSR and EEG are compared with designers’ subjective evaluations made by means of the NASA Task Load Index (Hart and Staveland, 1988). GSR and EEG measures are meant as proxies of mental stress and effort, respectively, and taken during a multi-stage design task. The most evident association that emerges is the one between self-rated mental effort and the power of the EEG beta-2 frequency band (20–30 Hz). Distinct formulations of design problems are investigated in Liu et al. (2018). Here, EEG is used during participants’ approaching open-ended, decision-making, and constrained design statements. The former are found to impact on temporal and occipital brain regions in the alpha frequency band, whereas constrained tasks result in the highest mental workload while heightening the activation of centroparietal and parietooccipital regions. Evaluations of design outcomes, assessed in terms of creativity metrics, reveal that high levels of novelty are significantly associated to the activation of the frontal, frontocentral, and occipital regions while being unsurprisingly found for open-ended tasks.

Conversely, emotions are a core topic in Liu et al. (2014). Here, multiple signals (EEG, GSR, and ECG) are acquired while engineering designers interact with a CAD system. The combination of these signals is interpreted in terms of key emotions, while different CAD tasks are distinguished based on the log of the CAD system. The emotions resulting from the neurophysiological devices are then checked with the designers participating in the experiment who, in a first version of the experimental design, express their agreement or disagreement with the outcomes and, then, rate their emotions with a questionnaire. In both cases, a substantial agreement between measures and subjective evaluations is found. The concept is extended in Sivanathan et al. (2015), in which a ubiquitous system is presented for acquiring metadata during the use of a CAD system. Despite many biometric tools are here included, the focus of the manuscript is neither on designers nor on the design process and, as such, will be not considered in further analyses.

---

**Table 6. Characterization of experiments concerning design processes or designers’ cognition, and addressing the search for a link between biometric data and variables extracted with traditional methods**

| Source                     | Number of Participants | Background of Designers                                      | Task                                                   | Stimulated task | Different Elicitation Methods | Data Analysis                  |
|----------------------------|------------------------|-------------------------------------------------------------|--------------------------------------------------------|-----------------|-------------------------------|-------------------------------|
| Liu et al. (2018)          | 19                     | Graduate Students from Engineering schools                  | Ideation, Problem-Solving (well-defined), Problem-Solving (ill-defined), Decision-Making, Sketching or manually drawing | Yes             | Assessing task performances  | Correlations, Descriptive statistics, ANOVA |
| Nguyen and Zeng (2017)     | 33                     | Engineering Students                                        | Ideation, Problem-Solving (ill-defined), Sketching or manually drawing | No              | Questionnaire                 | Statistical tests             |
| Petkar et al. (2009)       | 4                      | Not defined group of designers                              | Decision-Making, Non design-related task               | No              | Assessing task performances  |                               |

**Table 7. Characterization of experiments concerning design processes or designers’ cognition, in which hypotheses are formulated as for the relationship between biometric data and variables extracted with traditional methods**

| Source                     | Number of Participants | Background of Designers                                      | Task                                                   | Stimulated task | Different Elicitation Methods | Data Analysis                  |
|----------------------------|------------------------|-------------------------------------------------------------|--------------------------------------------------------|-----------------|-------------------------------|-------------------------------|
| Bi et al. (2015)           | 20                     | Graduate Students from Engineering schools                  | Problem-Solving (well-defined), Decision-Making, Non design-related task | Yes             | Interview, Assessing task performances | Correlations                  |
| Nguyen et al. (2015)       | 7                      | Not defined group of designers                              | Ideation                                               | No              | Questionnaire, Video Analysis |                               |
Differently from the above experiment, Nguyen et al. (2015) lever-
aged design tasks. The latter are characterized by different length
and degrees of hardness, which is subjectively assessed by the par-
ticipants. The hypothesis, confirmed by the results, concerns the
verification of the capability of EEG data to predict the perceived
hardness. More specifically, the scholars introduce in design stud-
ies a new measure, namely the transient microstate percentage,
borrowed from research in neurological diseases. The measure
takes into consideration the directional rapid variations of the
scalp field from one quasi-stable configuration to the next one.

Experiments classified as “Confirmation of hypotheses”

Bi et al. (2015) present an experiment with designers to infer their
weighing of different information stimuli. The participants are
asked to solve algebraic problems supported by graphical and
analytical information, whose attention toward is monitored
through an ET system. The results show that the designers with
analytical information, whose attention toward is monitored
asked to solve algebraic problems supported by graphical and
weighing of different information stimuli. The participants are
experience. Sun et al. (2018) present an experiment with designers to infer their
evaluation of performances of designers with diverse levels of
dergovers. Goucher-Lambert et al. (2018) (2015) present an experiment with designers to infer their
experience, use of stimuli and leveraging of analogies

A number of contributions belonging to this category regard the
evaluation of performances of designers with diverse levels of
experience. Sun et al. (2013) test the effect of introducing text
in stimuli for idea generation among novices and experts, while
their EEG was registered. Some participants receive a text as an
input, while the others belong to the control groups. Outcomes
are evaluated in terms of both the EEG activation and the creativ-
ity evaluation of generated ideas. Experts show similar thinking
patterns and this result in higher-quality ideas. In terms of activa-
tion patterns, novices exhibit greater differences when the text was
provided, especially in the right hemisphere of the brain. In Hu
and Reid (2018), the mutual relationships are investigated
between distraction, use of working memory, contextual experi-
ence and design outcomes assessed in terms of quantity, quality
and novelty. The low levels of cortical arousal detected by EEG
feature here the taking place of distraction or defocused attention.
The EEG headset and the corresponding software application
used in the experiments are claimed to be able to assess working
memory. The scholars demonstrate that the designers' level of dis-
traction is inversely related to contextual experience, while no sig-
ificant correlation was found between working memory and
temporal experience. The latter is negatively correlated with
mental states ascribable to creative endeavors beyond novelty of
ideas. A different neurophysiological tool for brain monitoring
used in Shealy et al. (2017), namely fNIRS. The contribution
studies the mental processes of freshmen and senior engineering
students while designing. The findings show that freshmen
require a much greater cognitive activation to generate solutions,

Experiments classified as “Additional data”

Experience, use of stimuli and leveraging of analogies

Table 8. Characterization of experiments concerning design processes or designers’ cognition, in which biometric data and variables extracted with traditional methods are extracted to provide a comprehensive description of the studied phenomenon

| Source                           | Number of Participants | Background of Designers | Task                        | Stimulated task | Different Elicitation Methods | Data Analysis       |
|----------------------------------|------------------------|-------------------------|-----------------------------|----------------|-------------------------------|---------------------|
| Cao et al. (2018)                | 43                     | Expert Designers, Novice Designers | Ideation, Sketching or manually drawing | Yes            | Interview, Assessing task performances | ANOVA               |
| Goucher-Lambert et al. (2018)    | 21                     | Graduate Students from Engineering schools | Ideation | Yes | Questionnaire, Interview, Assessing task performances | Regression Analysis, Descriptive statistics, ANOVA |
| Hess et al. (2017)               | 12                     | Engineering Students | Problem-Solving (well-defined) | No | Assessing task performances, Think-Aloud Method |                       |
| Hu and Reid (2018)               | 33                     | Engineering Students | Ideation, Problem-Solving (ill-defined), Sketching or manually drawing | No | Questionnaire, Assessing task performances | ANOVA               |
| Lohmeyer and Meboldt (2015)      | 26                     | Engineering Students | Observing technical drawings | No | Questionnaire, Assessing task performances, Think-Aloud Method |                       |
| Mussgnug et al. (2015)           | 25                     | Graduate Students from Engineering schools | Decision-making | No | Questionnaire, Video Analysis | Descriptive statistics |
| Shealy et al. (2017)             | 23                     | Engineering Students (beginners and advanced) | Ideation | No | Assessing task performances, Think-Aloud Method | Statistical tests |
| Petkar et al. (2009)             | 4                      | Not defined group of designers | Decision-Making, Non design-related task | No | Assessing task performances |                       |
Table 9. Characterization of experiments concerning design processes or designers’ cognition, in which biometric data are used and the outputs of subjective assessments are absent or neglected

| Source                        | Number of Participants | Background of Designers | Task                                      | Stimulated task | Different Elicitation Methods | Data Analysis          |
|-------------------------------|------------------------|-------------------------|-------------------------------------------|-----------------|------------------------------|------------------------|
| Alexiou et al. (2009)         | 18                     | Not defined group of designers | Problem-Solving (well-defined), Problem-Solving (ill-defined) | No              | Interview                    | Statistical tests      |
| Boa and Hicks (2016)          | 42                     | Graduate Students from Engineering schools | Problem-Solving (well-defined), Decision-Making | Yes             |                              | Regression analysis    |
| Colaco and Acartürk (2018)    | 38                     | Graduated Students from Architecture schools | Decision-Making | No              | Interview                    | Descriptive statistics |
| Liang et al. (2017)           | 15                     | Expert Designers        | Non design-related task                   | Yes             | Interview                    | ANOVA                  |
| Liang et al. (2018)           | 24                     | Expert Designers, Novice designer | Non design-related task                   | Yes             | Questionnaire, Interview     | Statistical tests, Correlations |
| Liu et al. (2014)             | 15                     | Engineering Students    | Using CAD                                 | No              | Questionnaire                | Fuzzy Sets             |
| Liu et al. (2016)             | 32                     | Engineering Students    | Ideation, Problem-Solving (ill-defined), Sketching or manually drawing, Evaluating and deciding | No              | Questionnaire                | PCA                    |
| Lohmeyer et al. (2013)        | 8                      | Engineering Students (beginners and advanced) | Observing technical drawings               | No              |                              |                        |
| Majdic et al. (2017)          | 9                      | Engineering Students    | Problem-Solving (well-defined)            | No              |                              | Correlations            |
| Nguyen and Zeng (2010)        | 1                      | Graduate Students from Engineering schools | Problem-Solving (well-defined), Sketching or manually drawing | No              | Video Analysis               |                        |
| Nguyen and Zeng (2014a)       | 28                     | Engineering Students    | Sketching or manually drawing, Non design-related task | Yes             | Questionnaire, Video Analysis |                        |
| Nguyen and Zeng (2014b)       | 11                     | Graduate Students from Engineering schools | Ideation                                  | No              | Video Analysis               | Statistical tests      |
| Nguyen et al. (2013)          | 11                     | Graduate Students from Engineering schools | Ideation, Problem-Solving (ill-defined), Sketching or manually drawing | No              | Assessing task performances, Video Analysis | Descriptive statistics, ANOVA |
| Nguyen et al. (2018)          | 8                      | Not defined group of designers | Ideation, Problem-Solving (ill-defined), Sketching or manually drawing | No              |                              |                        |
| Nguyen et al. (2019)          | 8                      | Not defined group of designers | Ideation, Problem-Solving (ill-defined), Sketching or manually drawing | No              | Video Analysis               | Correlations            |
| Ruckpaul et al. (2014)        | 15                     | Engineering Students    | Observing Technical Drawings              | Yes             | Questionnaire, Assessing task performances, Think-Aloud Method | Descriptive statistics |
| Ruckpaul et al. (2015)        | 34                     | Expert Designers, Novice Designers | Observing Technical Drawings              | No              | Assessing task performances, Think-Aloud Method | Statistical tests, Descriptive statistics |

(Continued)
as revealed by their degree of activation in the dorsolateral prefrontal cortex. Likewise, significant differences are also found in terms of traditional creativity metrics, especially the quantity of solutions.

Cao et al. (2018) deal with idea generation and analogical distance, i.e. the degree of unrelatedness between two or more concepts. Here, the investigated subjects are beginning and advanced students, who are involved in a design task and are contextually monitored with an ET system. The tasks undergo a subsequent evaluation and retrospective interviews are conducted to find relationships between the analogical distance of stimuli from the context of the design task, expertise, design fixation, and ET measures. The results show beginners’ inclination to gaze at far-distant stimuli, although these are not treasured in the proposed solutions, and to have larger numbers of saccades between stimuli characterized by a different analogical distance. The percentage of fixations across stimuli with different analogical distances fails to characterize students’ experience. The concept of analogical distance is focused on in Goucher-Lambert et al. (2018) too. This experiment includes the use of an fMRI scanner, in which a series of open-ended design tasks are performed by participants. Three different conditions are explored, namely the absence of stimuli, the provision of near and far stimuli. fMRI activations unveil two dissociable brain networks recruited during stimulated and non-stimulated design tasks, respectively; the former is featured by the activation of several temporal brain regions.

### Use, function, and representation of technical systems

The experiments presented in this subsection deal primarily with the development of design and engineering skills for students. In these contributions authored by a research group at the Swiss Federal Institute of Technology in Zurich, the use of ET glasses, in conjunction with other or alternative methodologies, enables the evaluation of tasks and the recognition of human activities beyond the provision of classical measures, such as saccades and fixations.

Lohmeyer and Meboldt (2015) involve engineers in their experiment and ask them to try to understand a sectional representation of a mechanical assembly. The analysis of ET data, supported by audio and the outcomes of the task, leads to the definition of participants’ behaviors in terms of skimming and scrutinizing sequences. The former are featured by short fixations and long saccades aimed to gain an overall grasp of the system. The latter includes long fixations and short saccades targeting the understanding of detail aspects. In Hess et al. (2017), mechanical engineering students are asked to disassemble a technical system, describe it, and infer its function. ET allows the scholars to individuate the components resulting critical for the correct explanation of the functioning of the assembly. The results show that low performers followed an observation pattern substantially differing from the flow line of force characterizing the system. The core objective of the study presented by Mussgnug et al. (2015) is to assess the usefulness of ET videos for the scope of understanding user-product interaction. The operation of an individual using a new fastening tool for the first time was recorded with both ET glasses and a video camera, which provide a first- and third-person perspective, respectively. Videos are then analyzed by engineering students, who are able to reveal a greater number of usability issues when ET recordings are made available.

### Experiments classified as “Alternative”

#### Designers’ cognition, mental states and brain activation in design tasks

In this subsection, a number of works are presented that deal with cognitive activities of designers in distinct tasks and conditions. The latter are identified based on the design of the experiment (distinct tasks or different formulations thereof) or in virtue of the use of specific instruments or methods, mainly videos. As achievable from the text and the references, a predominant number of contributions stem from a research group at the Concordia University, which has authored, by the way, articles described in previous subsections concerning the study of designers and design processes.

The contribution provided by Alexiou et al. (2009) can be considered as the starting point for the study of design neurological basis. In their experiment, the scholars leverage closed- and open-ended problems assigned to designers, who are monitored by means of an fMRI scanner. Particular differences are found between the initial part of the tasks, in which instructions are given and referred to as study phase, and the actual execution of tasks, performance phases. The study phase shows significantly enhanced activation in brain areas associated with the coordination of the movement, touch, and the integration of sensory perception. In contrast, the performance phase results in heightened activation in brain areas associated with high-level cognitive processing, visualization, and language. Convergent and divergent design phases are focused on also in Steinert and Jablokow (2013), which presents a proof of concept and a pilot experiment.

| Source                  | Number of Participants | Background of Designers              | Task                        | Stimulated task | Different Elicitation Methods | Data Analysis            |
|-------------------------|------------------------|--------------------------------------|-----------------------------|-----------------|------------------------------|--------------------------|
| Shealy et al. (2018)    | 12                     | Graduate Students from Engineering schools | Ideation                   | Yes             |                              | Correlations, ANOVA      |
| Steinert and Jablokow (2013) | Not defined group of designers | Problem-Solving (well-defined), Problem-Solving (ill-defined), Sketching or manually drawing | No                          | Video Analysis              |                           |
to link design activities, designers’ psychological mindsets, and physiological measures from EEG and ECG. The preliminary results support the possibility to discern convergent and divergent activities by means of physiological data. With a similar approach, the capability of distinguishing design activities and their characteristics by means of neurophysiological measures (and markedly EEG) is challenged in order to find alternatives to time-consuming protocol analyses by Nguyen and colleagues. A first attempt is discussed in Nguyen and Zeng (2010), where distinct activation networks are found for different design segments, namely problem analysis, solution evaluation, solution generation, and solution expression. The attention is shifted to the differences between creative and non-creative tasks in Nguyen and Zeng (2014a). The experiment reveals that activation in the beta range is higher for creative stages, which are contextually associated with a major commitment of the designer. Liu et al. (2016) associate EEG bands and design activities benefitting from Principal Component Analysis for data reduction. The findings show a specific band, namely alpha, is highly correlated with the designer’s resting in contrast to high-frequency bands associated with more active design segments. This stream of studies has so far reached maturation in Nguyen et al. (2019), in which EEG-based algorithms are tested against manual segmentation of design activities. The most effective algorithm in terms of predicting design segments, based on microstate transitions already discussed in Nguyen et al. (2015), is almost indistinguishable than manual segmentation if specific statistical tools are used. However, because of the identification of different cognitive structures, algorithmic segmentation cannot be considered as a replacement for manual segmentation hitherto. Overall, the results support the utility of combining EEG and traditional protocols, which is claimed to provide additional information as for corresponding cognitive states during design segments, beyond reducing the need for time-consuming activities.

A further area of research is concerned with designers’ mental states. After having verified that HRV is a good proxy of mental stress by means of a reviewed Stroop test, Nguyen et al. (2013) equip with an ECG system a number of participants asked to perform some conceptual design tasks. According to the experiment outcomes, the monitored design activities are not correlated with levels of mental stress. The study is then extended to correlate the ECG-measured mental stress and EEG-measured mental effort in Nguyen and Zeng (2014b). In light of the outcomes, designers predominantly experience low- or medium-stress levels during the proposed conceptual design activities. The same levels feature higher mental effort if compared to high-stress conditions. Still with reference to conceptual design, Nguyen et al. (2018) use EEG to assess effort, fatigue, and concentration. Such an assessment is enabled by the results of previous scholars’ studies and markedly (Nguyen et al., 2015). Based on the outcomes of the experiment, “high levels of effort occur mostly at the beginning and at the end of the design process”, while some nuances of fatigue have a negative correlation with this pattern. High levels of concentration, specifically featured by the Beta power in channel FP1, are particularly observed when designers delete their previously created designs to propose new ones.

**Focus on methods relevant to design**

In Ruckpaul et al. (2014), two different think-aloud methods, that is concurrent and retrospective, are analyzed for the evaluation of a drawing of a technical system – actually, participants are asked to judge if the system works correctly. The findings show that the two methods, while performing differently in terms of the extracted content of the verbalization, do not show significant variations in terms of ET measures.

Alternative ideation methods are dealt with by Shealy et al. (2018), whose experiment is supported by the use of an fNIRS helmet, which measures blood oxygenation in the prefrontal cortex. Participants face a design task without methodological support (individual brainstorming), using morphological analysis and TRIZ; the three conditions are clearly featured by different levels of methods’ structuredness. Particular differences among the three are found in terms of cortical activation and markedly in the regions associated with spatial working memory, cognitive flexibility, and abstract reasoning. More in detail, a high level of oxygenation in said areas is observed in brainstorming activities at the beginning of the design task, but this process is not sustained; this aspect represents a clear difference with respect to morphological analysis and TRIZ. These two methods, and more remarkably TRIZ, are also featured by a higher density of coordination among brain regions, which the scholars tend to associate with a more considerable cognitive effort. The difference between morphological analysis and TRIZ is identified in the fact that the former gives rise to substantial activation in the left hemisphere and the latter in both the left and middle hemispheres.

**Effects of stimuli and information**

Peculiar aspects of the design process are under the lens in this subsection. With the support of an ET system, Boa and Hicks (2016) monitor the variation of the ratio between saccades’ amplitudes and fixations’ length when engineers are administered with iconic or symbolic information. Low and high ratios are interpreted as focal and ambient styles, respectively. For instance, it is found that the prevailing style differs according to the kind of information when participants are in the process of finding such information. In contrast, the phase of familiarizing with information is featured by an ambient style in all the circumstances. Overall, the preliminary results suggest that the proposed ratio proves to be a good candidate to discriminate the different phases experienced by designers dealing with information. Pictorial representations are treated in Liang et al. (2017) too. Here, the provided stimuli are in the form of different artists’ works, featured by specific styles. Participants are asked to indicate a design project after exposure while being monitored by EEG. While the diverse works and styles are not discriminant for brain activation, different phases of the experiment are responsible for significant differences. In particular, designers’ engagement in visual attention (association) is linked to the activation of the frontoparietal (prefrontal, frontocentral, and parietooccipital) region(s). In a subsequent study (Liang et al., 2018), the procedure is somehow reversed, as, first, an ongoing project is described by the designer and, then, a matching of that project with an artwork (to be selected) is carried out – the employment of an EEG headset stays unchanged. The objective is the study of conceptual imagination, which leads to unveil how, for designers involved in web-supported activities, this phenomenon leads to notable brain activations in the prefrontal and temporal brain regions. Differences are particularly evident in the theta and alpha bands in the prefrontal regions between novice and expert designers, where the latter show overall higher spectral power. The comparison between different groups of individuals is at the core of the experiments presented in the next paragraph too.
Comparison of designers with different backgrounds and experience

With reference to the analysis of technical drawings and verbalization processes, Ruckpaul et al. (2015) highlight the differences between novice and expert engineering designers with the support of a remote ET. Here, it is assumed that short fixations feature the identification of mechanical components, while they are analyzed when long fixations take place. The results show that expert engineers carry out more in-depth analyses of technical systems with greater attention on the context and the system embodiment, while novices exhibit problems in describing the way parts interact and contribute to the whole system, although these parts are correctly characterized. A different kind of drawings, that is architectural drawings, is analyzed in Colaço and Acartürk (2018). Architects and people with a different background, monitored by a remote ET, are asked to interpret and evaluate couples of projects, which are shown by means of multiple representations. A particular difference between the two groups is found as non-architects exhibit longer fixations, longer total gaze times and more shifts between AOIs, which is interpreted as an inordinate behavior.

Eventually, the scope of the experiment presented in Majdic et al. (2017) is to map the cognitive load in design processes and identify the main traits that distinguish novice and advanced engineering students. The study, conducted by means of EEG, reveals that differences between the two groups of participants do not hold statistical significance, although, on average, less experienced students unsurprisingly display higher cognitive load.

Elaboration of gathered information and discussions

Intensity of research

The construction of the sample makes it possible to infer the intensity of the research conducted so far and some trends. In particular, all the contributions have been characterized by their publication year to obtain the diagrams that follow. It is worth noting that the data about the last few years (especially 2018) might be incomplete, while 2019 was not considered at all. Figure 2 shows the number of analyzed contributions per year and distinguishes experiments focused on evaluators and designers (lines featuring the stacked areas in the background), along with the four main classes in which experiments have been classified (histograms, see the legend). As mentioned, recent years are characterized by a growing number of presented design experiments with biometric measurements with the sole exception of the year 2016. In particular, it is possible to infer qualitatively that the number of experiments that make reference to subjective evaluations (red and orange columns in Fig. 2) is being overtaken by those (yellow and green columns) for which the confidence in the use of biometric devices is supposedly higher, that is “Additional data” and “Alternative”.

Subsequently, cumulative numbers of contributions have been used to build logistic curves through the online application Loglet Lab 4. Like in other studies, e.g. Borgianni et al. (2018), the S-shaped pattern of growth can be considered indicative of the future intensity of research. Figure 3 shows the curves corresponding to evaluators and designers – it is interesting to notice that the latter will be expectedly investigated more intensively in the coming years as opposed to the last few years. Based on trajectories, studies on designers are currently in the middle of a consistent growth phase, while experiments with evaluators might undergo a reduced research intensity in the near future.

Comparative use of biometric data

As aforementioned, Table 1 includes the specific measures, variables, or outcomes that are leveraged in the reviewed experiments. These are presented in a synthesized form and the explanation of the experiments’ context (to be found in the previous two sections) is necessary for interpreting them correctly.

In particular, with regard to Table 1:

- The fifth column indicates the measure or measures associated with the biometric device (fourth column) that are benefitted from in the corresponding experiment. In some cases, the extracted measures are not directly used, and these are substituted by procedures, algorithms, methods, software elaborations, graphs, or qualitative observations. It is worth noting that a common name has been attributed to these measures when clearly identical or very similar (e.g., “number of fixations” and “fixation count”) and, therefore, the reported terms might not be found in the text of the corresponding source.
- The sixth column reports, where relevant and available, excerpts from the sources that document how variables have been calculated or specific measurement conditions. In a few cases, the authors have added some words (in italics) for clarification purposes. It is worth noting that acronyms presented in the fifth and sixth columns apply to the corresponding sources only and are not generalizable.
- The seventh column indicates the variables relevant to the design domain that are more closely matched with the biometric data. Those include both stimuli and terms extracted with non-biometric measurements, markedly subjective evaluations. Remarks in brackets briefly recall the contextual conditions for these variables. In the cases these variables are categorical, e.g. designers’ background, these have been expressed in terms of biometric data’s capability of distinguishing, predicting, featuring, or interpreting different categories. Some variables have been excluded from the list because of being considered too specific for the source’s domain of investigation and, therefore, poorly exploitable in future studies and comparable with other research experiments.
- The eighth column indicates, for continuous and discrete variables present in the seventh column, whether the relationship between biometric and design-related variables is inverse. These cases are checked with the letter X.
- The ninth column expresses the kind of relationship that takes place between biometric data and design-related variables. This can be “Observed”, if it results from a broad and non-focused investigation; “Proven” (“Not Proven”), when the relationship is hypothesized and (not) demonstrated; “Assumed”, if the relationship is taken for granted and the experiment’s results are discussed based on this assumption.

Table 1 shows that research is very fragmented in terms of the specific use of biometric measures and their corresponding interpretation or search for interpretations. Despite the attempt of making the names of extracted variables as uniform as possible, a large variety of different parameters is still present. The way those measures are used and manipulated substantially depends on the object of studies and experimental conditions. It is
possible, however, to find some commonalities in the origin of variables and in the rationale behind their use.

- In EEG, fMRI, fNIRS, the activation of different channels or brain areas diffusely features phenomena ascribable to stress, workload, effort, difficulty, and fatigue. In some experiments, aesthetics and preferences are juxtaposed to EEG signals; as for the latter, conflicts emerge in terms of the EEG variables describing the phenomenon in the best way. Other EEG indexes are put into relationship with attention, although this phenomenon is predominantly studied by means of ET in the design domain. Still, especially by means of EEG, it is possible to capture and distinguish peculiar behaviors that characterize people with different design experience. Specific signals recorded in different channels are also referable to distinct design activities, analysis tasks, or the use of peculiar design methods. Some indexes extracted from the analysis of spectral power have been associated with different emotions. The transformation of neurologic measures through specific algorithms has been conducted to study cognitive processes and psychological states more in details, beyond phenomena ascribable to preferences and choices.

- As for ET tools, variables associated with fixations (e.g., duration, number, frequency, percentage) are the most diffused. Fixations are often ascribed to people’s attention and engagement, and design features’ importance, attractiveness, impression, and novelty. As a result, fixations are proxies of preferences and/or efforts to extract relevant information for evaluation purposes. Attention, interest and cognitive activities are often investigated by analyzing variations in the pupil diameter, while saccades are linked to explorative behaviors. Exploration strategies are often supported by quantitative or qualitative analyses of AOIs and ET graphs; those strategies can lead to distinguish people’s experience and background. The analysis of eye blinks is not diffused.

- When it comes to bio-feedback sensors, GSR and HRV meters are the most diffused. As for the former, direct and transformed measures are not only linked to participants’ arousal and degree of emotions (as expected) but also to stress and mental effort.
As for the latter, focused phenomena similarly include arousal, excitement, and stress; specifically, these phenomena are diffusely linked with HR variations or inter-beat intervals. The use of other devices, such as ECG, is seldom found in design research.

**Main outcomes of the review and comments**

Tables 1–9 are meant to provide information about many aspects of the sample of analyzed experiments. Each of these aspects can lead to different considerations and any reader can scrutinize specific data independently. In the authors’ view, the following considerations can be drawn with particular reference to the contents and objectives of the experiments.

- The foci of the experiments are substantially aligned with the objectives emerging from theoretical research (see the first bullet list of the “Introduction” section). This is favored by some authorship overlaps between theoretical and experimental studies.
- With reference to the design fields in which biometric measures are used, it emerges that the use of biometric tools has failed so far to open up many new research directions. In most circumstances, when positive outcomes have been achieved, biometric tools have served the role of studying established design fields more insightfully and with more objective assessment methods. Probably, their (perceived) level of maturity is still considered insufficient to stimulate new research directions.
- Evaluators- and designers-based experiments differ considerably in terms of not only methods (as aforementioned) but also objectives. As such, it makes sense for future reviews to consider these two domains separately. Common areas of research regard the understanding of technical systems, the role of information in design, and the display of emotions.
- The research in the field is highly fragmented, which can contribute to engender the perception that the actual impact of biometric measurements in design research is still modest. In a few cases, it results evident that scholars have built upon previously generated knowledge; in these few circumstances, they predominantly capitalize on their own research. This process can be partially motivated by the numerous areas of research the present review has elucidated (hence non-overlapping scholars’ interests), and the presumable difficulty in repeating experiments in the same conditions.
- Despite this fragmentation, there is convergence of outcomes for some specific research objectives. Different experiments lead to the conclusion that preferences can be predicted by means of biometric devices; notably, a variety of ET and EGG measurements are good proxies of preferences and attractiveness. Supported objectives are likewise the determination of the mental workload. Another shared objective is to replace time-consuming human activities, and markedly design protocols, with neurophysiological measures; here, however, conclusions cannot be drawn yet, although outcomes are promising.
- As mentioned, a plurality of biometric devices and measures (included those achievable by means of the same tool) have been used to extrapolate and characterize some phenomena or variables relevant to design, e.g. preferences, attention, stress. On the one hand, this represents an advantage in terms of the multiple options available to study such phenomena. On the other hand, this might have contributed to the current absence of best practices in the use of biometric devices.
- The samples of participants are commonly limited to few tens. On the one hand, this underlies a relative difficulty in conducting experiments with very large samples, which makes the supposed problems in repeating others’ experiments more severe. On the other hand, this represents a limit to the validity and generalizability of the findings, including those supported by multiple experiments. In any case, this situation, along with the recalled fragmentation of studies, urges to create research communities or interest groups that share practices and objectives to enhance the reliability and repeatability of findings enabled by biometric measures.
- A few research groups have carried out a large share of the described experiments, as already mentioned in the review sections. They show a constant research commitment in light of the time interval in which they have published research results. Some groups have been active just in the past. The motivations behind failing to carry out and/or publish new experiments are worth investigating in order to avoid past errors and to understand what might prevent biometric measurements from becoming commonplace in design research. However, to this respect, the relative proximity of S-curves’ asymptotes and the foreseen total number of experiments (see Fig. 3) tend to reject the hypothesis of a widespread penetration in design research.
- Research is still at the laboratory level, as the number of industrial case studies or collaborations with industrial partners are negligible. This might be motivated by insufficient reliability and repeatability of results emerging from the use of biometric devices in design. Moreover, the intense research on designers’ cognition, which represents a fundamental area for the use of biometric measures, poorly lends itself to technological transfer.
- With respect to journals, no favorite outlet has been individuated for the analyzed experiments.

**Limitations**

The present study is inherently affected by some limitations – the most remarkable ones follow. First, the creation of the sample, despite the structured procedure to build it, has introduced subjectivity in the inclusion or exclusion of contributions. Much of the analyzed research is multidisciplinary, and the influence of computer science, consumer behavior and psychology is evident. In some cases, the experiments’ contribution to the design field is marginal with respect to other disciplines, although the corresponding papers are published in prestigious design journals or conferences. The extent of the impact on the design was not considered by the authors when dealing with the description of the experiments and the analysis of the research intensity. The characterization and classification of the contributions are likewise biased by a certain degree of subjectivity.

Second, the authors considered the devices mentioned in previous studies as biometric and neurophysiological. However, the categorization of these instruments is not completely acknowledged. The literature tends to distinguish them from tools and techniques that are to be considered behavioral, see example Katicic et al. (2015) and Desmet et al. (2016). These include, among others, the analysis of hand gestures, which complements biometric measurements in some of the described experiments, and Facial Expression Recognition, whose use is surfacing in design research as well, e.g. Bezawada et al. (2017). If the whole set of technologies capable of extracting inadvertent people’s reactions had to be considered, behavioral tools should be included in addition to biometric devices.
Eventually, the present state-of-the-art has failed to collect and illustrate experimental problems (poorly discussed in the reviewed contributions), which represents another candidate area for future work. Few preliminary indications are nevertheless given. Through a first reading of the analyzed papers, participants’ discomfort problems are not reported diffusely despite the widespread concerns about the invasiveness of (some) biometric devices. Conversely, many manuscripts report the compliance with institutional ethical guidelines and regulations, as well as the resorting to participants’ written agreements. Undoubtedly, the analysis of measures is often carried out with sophisticated techniques and data elaboration software, which represents an additional hindrance to the repeatability of the studies.

Outlook and final remarks

The present paper intends to represent a baseline for acquiring knowledge about the use of biometric and neurophysiological measures in design research. According to what can be inferred from the study, the discussed tools and measures are acquiring growing importance in the design domain, but they are likely to keep representing a niche in design research in the foreseeable future.

The paper has illustrated the pertinent contributions gathered so far and described objectives, methods, tools, and results of the corresponding manuscripts. The authors are aware that the presented situation might evolve quickly and that the sample of collected experiments might require updates soon. This is based not only on the trajectories of S-curves illustrated in Figure 3 but also on the authors’ knowledge of research groups that are finalizing their experiments and analyses. The increasing relevance of the topic is emphasized by the ongoing call for papers in the Thematic Collection “Design Neurocognition: Understanding of Design through Studies of the Brain” for the journal Design Science. Moreover, a large number of relevant contributions have been published during the review process of the present paper. These are not fully analyzed and described here, but they are summarized in Table 10, where role of participants, kind of experiment, and employed biometric instruments are indicated as well. Other recent publications aim to analyze with different methods already presented experimental results, e.g. Goucher-Lambert and McComb (2019) and Shealy and Gero (2019).

As a further contribution of the paper, a variety of classification criteria has been proposed for the analyzed experiments, which are deemed largely repeatable also in other reviews targeting experimental work in design. Due to space reasons, the authors have avoided explaining why each experiment has been classified in a certain way; readers can contact the corresponding author for details. Likewise, comments on the outcomes of the classifications are not reported for all the analyzed factors, but they are limited to the ones judged as the most interesting. To this respect, readers can easily form their own opinion by analyzing available tables. Still, for the sake of brevity, the paper has omitted basic knowledge about the functioning of specific biometric devices and their selection based on research objectives to be pursued. For a better comprehension of what is described in the paper, readers with little experience in the field might benefit from knowledge easily achievable from indicated references in the design field, specialized literature (especially in the medical field), but also the web at large. As mentioned above, the authors chose to privilege a wider description of the experiments over pieces of information easier to individuate.

Open research issues and angles that have not been dealt with in sufficient detail are presented in the “Discussion” section, which, along with the remarked limitations of the present study, represent triggers for future work. In brief, it emerges that the use of biometric tools and measures have demonstrated their utility and versatility in terms of involved design fields. The distinction into classes of experiments and their number over the years suggests that an increasing number of research groups is confident in the interpretability of biometric measures. The number of phenomena that can be investigated without the need to gather subjective indications is increasing and meaningful. However, the reliability and significance of design-related variables interpretable or measurable through biometric devices are uneven across design domains. In a few cases, the knowledge generated by means of biometric measurements can be considered established. The rejection of hypotheses that relate biometric measures and other variables has taken place in a considerable number of cases. In addition, the different approaches and the different biometric data used to assess similar phenomena have so far contributed to prevent the definition of best practices. Therefore, the remarkable variety of research objectives pursued in the reviewed experiments brings about a perception of fragmentation in the field. To this respect, the creation of design research communities interested in the use of biometric tools is fundamental to increase their maturity and popularity and, consequently, to contribute to reducing the reliance on subjective data in design research. In line with Cross’ (2018) viewpoint on experimental design research, sharing experiments and repeating them in different research groups might be the key to prove the effectiveness of biometric measurements and the reliability of the corresponding interpretations. Undoubtedly, this is hindered by the fact that, in many cases, research groups have planned experiments based on specific interests and included biometric tools to support the achievement of relevant results, whereas biometric measurements were not the objective of the studies per se.

| Source of the experiment | Role of participants | Kind of experiment | Biometric Tool |
|--------------------------|----------------------|--------------------|----------------|
| Hay et al. (2019)        | Designers            | Additional data    | fMRI           |
| Kalantari (2019)         | Evaluators           | Additional data    | EEG, HRV, GSR  |
| Laspia et al. (2019)     | Designers            | Alternative        | EEG, Remote ET |
| Reimlinger et al. (2019) | Designers            | Additional data    | ET glasses     |
| Self (2019)              | Designers            | Additional data    | Remote ET      |
| Vieira et al. (2019)     | Designers            | Alternative        | EEG            |
| Wang et al. (2019)       | Evaluators           | Additional data    | EEG            |
| Zhao and Zeng (2019)     | Designers            | Alternative        | HRV            |
Acknowledgements. The study is conducted in the frame of the project EYE-TRACK funded by the Free University of Bozen-Bolzano with the call CRC2017. This work was supported by the Open Access Publishing Fund of the Free University of Bozen-Bolzano.

References

Abdipour M, Lorentzen L and Olin H (2016) A design research lab—an integrated model to identify conscious and unconscious behavior in the design process. In Di Bucchianico G and Kercher P (eds), Advances in Design for Inclusion. Cham: Springer, pp. 553–563.

Alexiou K, Zamenopoulos T, Johnson JH and Gilbert SJ (2009) Exploring the neurological basis of design cognition using brain imaging: some preliminary results. Design Studies 30, 623–647.

Aurup GM and Akgunduz A (2012) Pair-wise preference comparisons using alpha-peak frequencies. Journal of Integrated Design and Process Science 16, 3–18.

Balters S and Steinert M (2017) Capturing emotion reactivity through physiology measurement as a foundation for affective engineering in engineering design science and engineering practices. Journal of Intelligent Manufacturing 28, 1585–1607.

Bettis RA, Ethiral S, Gambardella A, Helfat C and Mitchell W (2016) Creating repeatable cumulative knowledge in strategic management: a call for a broad and deep conversation among authors, referees, and editors. Strategic Management Journal 37, 257–261.

Bezawada S, Hu Q, Gray A, Brick T and Tucker C (2017) Automatic facial feature extraction for predicting designers’ comfort with engineering equipment during prototype creation. Journal of Mechanical Design 139, 021102.

Bi Y, Shergadwala M, Reid T and Panchal JH (2015) Understanding the utilization of information stimuli in design decision making using eye gaze data. ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Paper No. V02AT03A017, Boston, Massachusetts, USA, August 2–5.

Boa DR and Hicks B (2016) Discriminating engineering information interaction using eye tracking and an information operations model. DS 84: Proceedings of the DESIGN 2016 14th International Design Conference, Dubrovnik, Croatia, May 16–19, pp. 1–10.

Boa D, Hicks B and Nasaei A (2013) A comparison of product preference and visual behaviour for product representations. DS 75–7: Proceedings of the 19th International Conference on Engineering Design (ICED13), Vol. 7, Seoul, Korea, August 19–22.

Boa DR, Ranscombe C and Hicks B (2015) Determining the similarity of products using pairwise comparisons and eye tracking. DS 80–5: Proceedings of the 20th International Conference on Engineering Design (ICED 15), Vol. 5, Milan, Italy, July 27–30.

Borgianni Y, Cascini G and Rotini F (2018) Investigating the future of the fuzzy front end: towards a change of paradigm in the very early design phases? Journal of Engineering Design 29, 644–664.

Borgianni Y, Maccioni L and Basso D (2019) Exploratory study on the perception of additively manufactured end-use products with specific questionnaires and eye-tracking. International Journal on Interactive Design and Manufacturing 13, 743–759.

Burlamaqui L and Dong A (2017) Eye gaze experiment into the recognition of intended affordances. ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Paper No. V007T06A026, Cleveland, Ohio, USA, August 6–9.

Camm AJ, Malik M, Bigger JT, Breithardt G, Cerutti S, Cohen RJ, Counel P, Fallen EL, Kennedy HL and Kleiger RE (1996) Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Circulation 93(5), 1043–1065.

Cao J, Xiong Y, Li Y, Liu L and Wang M (2018) Differences between beginning and advanced design students in analogical reasoning during idea generation: evidence from eye movements. Cognition, Technology & Work 20, 1–16.

Carbon CC, Hutzler F and Minge M (2006) Innovativeness in design investigated by eye movements and pupillometry. Psychology Science 48, 173–186.

Cash P, Stankovic T and Štorga M (2016) An introduction to experimental design research. In Cash P, Stankovic T and Štorga M (eds), Experimental Design Research. Cham: Springer, pp. 3–12.

Colaco CA and Acartürk C (2018) Visual behaviour during perception of architectural drawings: differences between architects and non-architects. In Gero JS (ed.), Design Computing and Cognition DCC18. Heidelberg: Springer, pp. 417–436.

Cross N (2018) Developing design as a discipline. Journal of Engineering Design 29, 691–708.

de Groot AD (2014) The meaning of “significance” for different types of research [translated and annotated by Eric-Jan Wagemakers, Denny Borsboom, Josine Verhagen, Rogier Kivot, Marijan Bakker, Angelique Cramer, Dora Matzke, Don Mellenbergh, and Han J van der Maas]. Acta Psychologica 148, 188–194.

Desmet PM, Vestenburg MH and Romero N (2016) Mood measurement with Pick-A-Mood: review of current methods and design of a pictorial self-report scale. Journal of Design Research 14, 241–279.

Dinari M, Summers JD, Shah J and Park YS (2016) Evaluation of empirical design studies and metrics. In Cash P, Stankovic T and Štorga M (eds), Experimental Design Research. Cham: Springer, pp. 13–39.

Dogan KM, Suzuki H and Gunpinar E (2018) Eye tracking for screening design parameters in adjective-based design of yacht hull. Ocean Engineering 166, 262–277.

Du P and MacDonald EF (2014) Eye-tracking data predict importance of product features and saliency of size change. Journal of Mechanical Design 136, 081005.

Du P and MacDonald EF (2015) Products’ shared visual features do not cancel in consumer decisions. Journal of Mechanical Design 137, 071409.

Du P and MacDonald EF (2018) A test of the rapid formation of design cues for product body shapes and features. Journal of Mechanical Design 140, 071102.

Dykes TH, Rodgers PA and Smyth M (2009) Towards a new disciplinary framework for contemporary creative design practice. CoDesign 5, 99–116.

Ergan S, Radwan A, Zou Z, Tseng HA and Han X (2019) Quantifying human experience in architectural spaces with integrated virtual reality and body sensor networks. Journal of Computing in Civil Engineering 33, 04018062.

Georgiev GV, Yamada K and Taura T (2017) Dynamics of shifting viewpoints: an investigation into users’ attitudes towards products. Journal of Design Research 15, 62–84.

Goucher-Lambert K and McComb C (2019) Using hidden Markov models to uncover underlying states in neuroimaging data for a design ideation task. Proceedings of the Design Society: International Conference on Engineering Design, Vol. 1. Cambridge University Press, pp. 1873–1882.

Goucher-Lambert K, Moss J and Cagan J (2019) A neuroimaging investigation of design ideation with and without inspirational stimuli—understanding the meaning of near and far stimuli. Design Studies 60, 1–38.

Guo F, Ding Y, Liu W, Liu C and Zhang X (2016) Can eye-tracking data be measured to assess product design?: visual attention mechanism should be considered. International Journal of Industrial Ergonomics 53, 229–235.

Guo F, Li M, Hu M, Li F and Lin B (2019) Distinguishing and quantifying the visual aesthetics of a product: an integrated approach of eye-tracking and EEG. International Journal of Industrial Ergonomics 71, 47–56.

Hart SG and Staveland LE (1988) Development of NASA-TLX (Task Load Index): results of empirical and theoretical research. Advances in Psychology 52, 139–183.

Hey L, Duffy AHB, Grealy M, Tahsiri M, McTeague C and Vuletic T (2019) A novel systematic approach for analysing exploratory design ideation. Journal of Engineering Design, in press.

He C, Ji Z and Gu J (2017) Research on the effect of mechanical drawings’ different marked way on browse and search efficiency based on eye-tracking technology. International Conference on Man-Machine-Environment System Engineering 456. Singapore: Springer, pp. 515–523.

Hess S, Lohmeyer Q and Meboldt M (2017) Utilization of mobile eye tracking data to improve engineering design education. DS 88: Proceedings of the
19th International Conference on Engineering and Product Design Education (E&PDE17), Oslo, Norway, September 7–8, pp. 002–007.

Hill AP and Bohli J (2016) Applications of optical neuroimaging in usability research. Ergonomics in Design 24, 4–9.

Ho CH and Lu YN (2014) Can pupil size be measured to assess design products? International Journal of Industrial Ergonomics 44, 436–441.

Hodes RL, Cook III EW and Lang PJ (1985) Individual differences in automatic response: conditioned association or conditioned fear? Psychophysiology 22, 545–560.

Hsu CC, Fann SC and Chuang MC (2017) Relationship between eye fixation patterns and Keanse evaluation of 3D chair forms. Displays 50, 21–34.

Hu WL and Reid T (2018) The effects of designers' contextual experience on the ideation process and design outcomes. Journal of Mechanical Design 140, 101101.

Hurley RA, Galvarino J, Thackston E, Ouzts A and Pham A (2013) The effect of modifying structure to display product versus graphical representation on packaging. Packaging Technology and Science 26, 453–460.

Hutzler F (2014) Reverse inference is not a fallacy per se: cognitive processes can be inferred from functional imaging data. Neuroimage 84, 1061–1069.

Hyun KH, Lee JH and Kim M (2017) The gap between design intent and user response: identifying typical and novel car design elements among car brands for evaluating visual significance. Journal of Intelligent Manufacturing 28, 1729–1741.

Ishak SMM, Sivaji A, Tzuan SS, Hussein H and Bujang R (2015) Assessing eye fixation behaviour through design evaluation of lawi ayam artefact. Jurnal Teknologi 77, 25–33.

Jenkins S, Brown R and Rutterford N (2014) Consumer neuroscience: assessing the brain response to marketing stimuli using electroencephalogram (EEG) and eye tracking. Expert Systems with Applications (2013) Consumer neuroscience: assessing the brain response to marketing stimuli using electroencephalogram (EEG) and eye tracking. Expert Systems with Applications 40, 3803–3812.

Kim J, Bouchard C, Ryu H, Omhover JF and Aoussat A (2012) Emotion finding a way to users from designers: assessing product images to convey designer’s emotion. Journal of Design Research 10, 307–323.

Köhler M, Falk B and Schmitt R (2015) Applying eye-tracking in Keanse engineering method for design evaluations in product development. International Journal of Affective Engineering 14, 241–251.

Kovář D, Brozovič M and Možina K (2018) Do prominent warnings make packaging less attractive? Safety Science 110, 336–343.

Kukkonen S (2005) Exploring eye tracking in design evaluation. Joining Forces 119–126.

Laspia A, Montagna F and Törlind P (2019) Contrasting divergent and convergent thinking by electroencephalography and eye tracking. Research into Design for a Connected World. Singapore: Springer, pp. 179–188.

Li BR, Wang Y and Wang KS (2017) A novel method for the evaluation of fashion product design based on data mining. Advances in Manufacturing 5, 370–376.

Li W, Wang L, Wang L and Jing J (2018) A model based on eye movement data and artificial neural network for product styling evaluation. Proceedings of the 24th International Conference on Automation & Computing, Newcastle upon Tyne, UK, 6–7 September 2018.

Liang C, Lin CT, Yao SN, Chang WS, Liu YC and Chen SA (2017) Visual attention and association: an electroencephalography study in expert designers. Design Studies 48, 76–95.

Liang C, Chang CC and Liu YC (2019) Comparison of the cerebral activities exhibited by expert and novice visual communication designers during idea incubation. International Journal of Design Creativity and Innovation 7, 213–236.

Liu Y, Ritchie JM, Lim T, Kosmadoudi Z, Sivanathan A and Sung RC (2014) A fuzzy psycho-physiological approach to enable the understanding of an engineer’s affect status during CAD activities. Computer-Aided Design 54, 19–38.

Liu Z, Ayen TA, Zeng Y and Hamza AB (2016) Identification of relationships between electroencephalography (EEG) bands and design activities. ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Paper No. V007T06A019, Charlotte, NC, USA, August 21–24.

Liu L, Li Y, Xiong Y, Cao J and Yuan P (2018) An EEG study of the relationship between design problem statements and cognitive behaviors during conceptual design. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 32, 351–362.

Lohmeyer Q and Meboldt M (2015) How we understand engineering drawings: an eye tracking study investigating skimming and scrutinizing sequences. International Conference on Engineering Design ICED, Vol. 15, Milan, Italy, July 27–30.

Lohmeyer Q and Meboldt M (2016) The integration of quantitative biometric measures and experimental design research. In Cash P, Stankovic T and Kovakova M (eds), Proceedings of the 16th International conference on Engineering and Product Design Education (E&PDE14), University of Twente, The Netherlands, September 04–05.

Lou S, Feng Y, Tian G, Lv Z, Li Z and Tan J (2017) A cyber-physical system for product conceptual design based on an intelligent psycho-physiological approach. IEEE Access 5, 5378–5387.

Maccioni L, Bortolani M and Basso D (2019) Value perception of green products: an exploratory study combining conscious answers and unconscious behavioral aspects. Sustainability 11, 1226.

Majdic B, Cowan C, Girdner J, Opoku W, Pierrakos O and Barrella E (2017) Monitoring brain waves in an effort to investigate student’s cognitive load during a variety of problem solving scenarios. Systems and Information Engineering Design Symposium (SIEDS), Charlottesville, VA, USA, April 28, IEEE, pp. 186–191.

Mougenot C, Watanabe K, Bouchard C and Aoussat A (2009) Visual materials and designers’ cognitive activity; towards in-depth investigations of design cognition. International Association of Societies of Design Research, Seoul, South Korea.

Mussgnug M, Lohmeyer Q and Meboldt M (2014) Raising designers’ awareness of user experience by mobile eye tracking records. DS 78: Proceedings of the 16th International conference on Engineering and Product Design Education (E&PDE14), University of Twente, The Netherlands, September 04–05.

Mussgnug M, Waldern MF and Meboldt M (2015) Mobile eye tracking in usability testing: designers analysing the user-product interaction. DS 80–2 Proceedings of the 20th International Conference on Engineering Design (ICED 15), Vol. 2, Milan, Italy, July 27–30, pp. 349–358.
Nguyen P, Singer D, Lohmeyer Q and Meboldt M (2017) Automated interpretation of eye–hand coordination in mobile eye tracking recordings. KI-Künstliche Intelligenz 31, 331–337.

Nagamachi M (1995) Kansai engineering: a new ergonomic consumer-oriented technology for product development. International Journal of Industrial Ergonomics 15, 3–11.

Nguyen TA and Zeng Y (2010) Analysis of design activities using EEG signals. ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Montreal, Quebec, Canada, August 15–18, pp. 277–286.

Nguyen TA and Zeng Y (2014a) A preliminary study of EEG spectrum of a single subject performing a creativity test. Innovative Design and Manufacturing (ICIDM). IEEE, pp. 16–21.

Nguyen TA and Zeng Y (2014b) A physiological study of relationship between designer’s mental effort and mental stress during conceptual design. Computer-Aided Design 54, 3–18.

Nguyen TA and Zeng Y (2017) Effects of stress and effort on self-rated reports in experimental study of design activities. Journal of Intelligent Manufacturing 28, 1609–1622.

Nguyen TA, Xu X and Zeng Y (2013) Distribution of mental stresses during conceptual design activities. DS 75–7: Proceedings of the 19th International Conference on Engineering Design (ICED13), Vol. 7, Seoul, Korea, August 19–22, pp. 287–296.

Nguyen P, Nguyen TA and Zeng Y (2015) Measuring the evolved hardness of design problems using transient microstates. ASME 2015 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Paper No. V007T06A029, Boston, MA, USA, August 2–5.

Nguyen P, Nguyen TA and Zeng Y (2018) Empirical approaches to quantifying effort, fatigue and concentration in the conceptual design process. Research in Engineering Design 29, 393–409.

Nguyen P, Nguyen TA and Zeng Y (2019) Segmentation of design protocol using EEG. Artificial Intelligence for Engineering Design, Analysis and Manufacturing 33, 11–23.

Papalambros PY (2010) The human dimension. Journal of Mechanical Design 132, 050201.

Park J, DeLong M and Woods E (2012) Exploring product communication between the designer and the user through eye-tracking technology. International Journal of Fashion Design, Technology and Education 5, 67–78.

Peruzzini M, Grandi F and Pellicciari M (2017) Benchmarking of tools for user experience analysis in industry 4.0. Procedia Manufacturing 11, 806–813.

Petkar H, Dande S, Yadav R, Zeng Y and Nguyen TA (2009) A pilot study to assess designer’s mental stress using eye gaze system and electroencephalogram. ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, San Diego, CA, pp. 899–909.

Reimlinger B, Lohmeyer Q, Morson R and Meboldt M (2019) A comparison of how novice and experienced design engineers benefit from design guidelines. Design Studies 63, 204–223.

Robinson MA (2016) Quantitative research principles and methods for human-focused research in engineering design. In Cash P, Stankovic T (eds), Experimental Design Research. Cambridge University Press, pp. 1833–1842.

Ruckpaul A, Fürstenhöfer T and Matthiesen S (2014) Combination of eye tracking and think-aloud methods in engineering design research. In Design Computing and Cognition DCC14. Cham: Springer, pp. 81–97.

Ruckpaul A, Nelius T and Matthiesen S (2015) Differences in analysis and interpretation of technical systems by expert and novice engineering designers. ASME 80-2 Proceedings of the 20th International Conference on Engineering Design (ICED 15), Vol. 2, Milan, Italy, July 27–30.

Russell JA (1980) A circumplex model of affect. Journal of Personality and Social Psychology 39, 1161–1178.

Schmitt R, Köhler M, Durá JV and Díaz-Pineda J (2014) Objectifying user attention and emotion evoked by relevant perceived product components. Journal of Sensors and Sensor Systems 3, 315–324.

Self JA (2019) Communication through design sketches: implications for stakeholder interpretation during concept design. Design Studies 63, 1–36.

Seshadri P, Bi Y, Bhataj J, Simons R, Hartley J and Reid T (2016) Evaluations that matter: customer preferences using industry-based evaluations and eye-gaze data. ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Paper No. V007T06A047, Charlotte, NC, USA, August 21–24.

She J and MacDonald EF (2018) Exploring the effects of a product’s sustainability triggers on pro-environmental decision-making. Journal of Mechanical Design 140, 011102.

Shealy T and Gero J (2019) The neurocognition of three engineering concept generation techniques. Proceedings of the Design Society: International Conference on Engineering Design, Vol. I. Cambridge University Press, pp. 1833–1842.

Shealy T, Grohs JR, Hu MM, Maczka DK and Panneton R (2017) Investigating Design Cognition during Brainstorming Tasks with Freshmen and Senior Engineering Students Using Functional Near Infrared Spectroscopy. Columbus, OH: ASEE.

Shealy T, Hu M and Gero J (2018) Patterns of cortical activation when using concept generation techniques of brainstorming, morphological analysis, and TRIZ. ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Paper No. V007T06A035, Quebec City, Quebec, Canada, August 26–29.

Sivanathan A, Lim T, Ritchie J, Sung R, Kosmadoudi Z and Liu Y (2015) The application of ubiquitous multimodal synchronous data capture in CAD. Computer-Aided Design 59, 176–191.

Steinert M and Jablokow K (2013) Triangulating front end engineering design activities with physiological data and psychological preferences. DS 75–7: Proceedings of the 19th International Conference on Engineering Design (ICED13), Vol. 7, Seoul, Korea, August 19–22, pp. 109–118.

Stroop JR (1935) Studies of interference in serial verbal reactions. Journal of Experimental Psychology 18, 643.

Sun L, Xiang W, Chai C, Wang C and Liu Z (2013) Impact of text on idea generation: an electroencephalography study. International Journal of Technology and Design Education 23, 1047–1062.

Suzianti A, Rengkung S, Nurijayho B and Al Rasyid H (2015) An analysis of cognitive-based design of yogurt product packaging. International Journal of Technology 6, 659.

Sykott B, Cagan J and Tabibnia G (2013) Understanding consumer tradeoffs between form and function through metacognition and cognitive neuroscience analyses. Journal of Mechanical Design 135, 101002.

Telpaz A, Webb R and Levy DJ (2015) Using EEG to predict consumers’ future choices. Journal of Marketing Research 52, 511–529.

Triberti S, Chirico A, La Rocca G and Riva G (2017) Developing emotional design: emotions as cognitive processes and their role in the design of interactive technologies. Frontiers in Psychology 8, 1773.

Ueda K (2014) Neural mechanisms of evaluation and memory of product. ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Paper No. V01AT02A087, Buffalo, NY, USA, August 17–20.

Vieira SL, Gero JS, Delmoral J, Gattol V, Fernandes C and Fernandes AA (2019) Comparing the design neurocognition of mechanical engineers and architects: a study of the effect of designer’s domain. Proceedings of the Design Society: International Conference on Engineering Design, Vol. 1. Cambridge University Press, pp. 1853–1862.
Wang H, Wang J, Zhang NN, Sun GB, Huang HL and Zhao HB (2010) Automobile modeling evaluations based on electrophysiology. Advanced Materials Research 118, 454–458.

Wang ZY, Liu HS, Shi HH and Liu H (2011) The research of automobile design evaluation method based on the eye tracking system technology. Advanced Materials Research 230, 654–658.

Wang P, Peng D, Li L, Chen I, Wu C, Wang X, Childs P and Guo Y (2019) Human-in-the-loop design with machine learning. Proceedings of the Design Society: International Conference on Engineering Design, Vol. 1. Cambridge University Press, pp. 2577–2586.

Yang X, He H, Wu Y, Tang C, Chen H and Liang J (2016) User intent perception by gesture and eye tracking. Cogent Engineering 3, 1221570.

Yilmaz B, Korkmaz S, Arslan DB, Güngör E and Asyalı MH (2014) Like/dislike analysis using EEG: determination of most discriminative channels and frequencies. Computer Methods and Programs in Biomedicine 113, 705–713.

Zhang JN, Du L, Xie Y and Zou FY (2014) A literature review of using eye tracking technology in fashion and product design. Applied Mechanics and Materials 556, 1662–1665.

Zhao M and Zeng Y (2019) Influence of information collection strategy on designer’s mental stress. Proceedings of the Design Society: International Conference on Engineering Design, Vol. 1. Cambridge University Press, pp. 1783–1792.

Zhao M, Yang D, Liu S and Zeng Y (2017) Mental stress-performance model in emotional engineering. Emotional Engineering 6, 119–139.

Yuri Borgianni has obtained a Master Degree in Mechanical Engineering (2005) and a PhD in Industrial Engineering (2014) at the University of Florence, Italy. He is currently an Assistant Professor at the Free University of Bozen/Bolzano, Italy, where he teaches "Technical Drawing and Industrial Engineering Methods", "Reverse Engineering and Rapid Prototyping", and "CAD Fundamentals." His research interests include design creativity, ideation techniques, human behavior in design, user-centered design, design for additive manufacturing, methods for conceptual design such as TRIZ, and eco-design. He is author of more than 60 articles published in scientific journals and international conferences.

Lorenzo Maccioni has obtained a Master Degree in Mechanical Engineering (2016) at the University of Florence, Italy. He is currently a PhD student in the program "Sustainable Energies and Technologies" at the Free University of Bozen/Bolzano, Italy. His research interests include eco-design, value-oriented product development, methods for conceptual design such as TRIZ, machine design, and additive manufacturing. He is author of more than 15 articles published in scientific journals and international conferences.