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Review

Biometric Analysis in Design Cognition Studies: A Systematic Literature Review

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Abstract: This study presents a systematic literature review on the utilisation of biometric analyses within the research area of design cognition. Design is a critical phase of many industries including architecture and construction, industrial design, engineering design, and many others. The development of design theories and methodologies to further understanding of designers' cognitive design processes is thereby crucial. Traditional methods for design studies such as protocol analysis are prone to subjective factors and rely upon designers' externalisations of their own design intentions, which typically makes such results difficult to validate. Design neuroscience has become an emerging area of research in recent years. Utilising biometric measurements such as electroencephalography (EEG), functional magnetic resonance imaging (fMRI) and eye-tracking, more objective data can be obtained about the physiological responses of designers during their performing of design activities, and such empirical data can then be analysed without relying on designers to self-report. Recent years have witnessed an increasing number of studies in that research area. However, there is a lack of comprehensive understanding about current design studies that utilise biometric analysis as well as the application and effectiveness of the analysis approach. Therefore, this research utilised a systematic literature review method, reviewing the past decade's biometric analysis studies related to design cognition, aiming to bridge the research gap areas as informed by the systematic review. The findings of this study suggest that this research area is still at an early stage, and there has accordingly been a trend of increasing publications within the field. Most design neuroscience studies have investigated the common areas such as design problem solving, design creativity, design thinking strategies, cognitive load and visual attention. Further research is especially needed in the following: (i) design neuroscience studies for various digital design environments; (ii) practical applications of biometric analysis design studies to both design practice and design education; and (iii) further advancement of biometric techniques applicable to future design studies. The results of this study contribute to a more comprehensive understanding of the existing knowledge and research about the application of biometric analysis to design cognition studies; this is potentially beneficial to future design research and education, and it leads to more advanced application of design cognition studies.

Keywords: biometric analysis; design cognition; systematic literature review

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1. Introduction and Background

Design cognition can be described as studies of phases of the design process, encompassing theoretical models of high-level cognition and multimodal behaviour [1,2]. Some scholars categorise design processes into the four contributing sub-tasks of problem analysis, solution evaluation, solution generation, and solution expression [3,4], while others describe the design process as formulation, analysis, synthesis, evaluation, reformulation and documentation [5]. Researchers argue that progression through these phases occurs in a cyclic manner, as the designer assesses the design problem and obtains an intuitive solution before higher levels of analysis overcome initial solution generations until the most appropriate solution is determined [1,6].

The development of design theories and methodologies for increasing understanding of designers' cognitive behaviour is crucial. Traditionally, the most dominant method used in design studies is protocol analysis; however, that method is susceptible to more subjective factors and usually relies upon designers' externalisations of their design intention, which makes the results difficult to validate. Design neuroscience is an emerging research area in recent years, investigating the underlying neural processes of designers' behaviour, using a convergence of research methods from design cognition and neuroscience, including common biometric measures such as electroencephalography (EEG), functional magnetic resonance imaging (fMRI), and eye-tracking (of fixation and gaze patterns).

Using the most common measurement tool preference within the field, EEG technology relies on analysing brain activities and human behaviour by measuring the frequencies of brain signals [7,8]. EEG recordings categorise bands of neural activity according to delta, theta, alpha, beta, and gamma labelled frequency ranges to reflect communication changes between different neural regions, while a designer progresses through their design process [2,9–12]. While such EEG techniques are useful for temporal investigations measuring time-related tasks, alternative imaging methods such as fMRI can use spatial resolution to identify specific neural regions where such activation patterns and changes in cerebral blood flow are detected [13–16]. Functional near-infrared spectroscopy (fNIRS) is also a developing biometric technique in the design research field, with some similarities to fMRI; however, fNIRS can be conducted in a more natural experiment setting compared to fMRI, and fNIRS is more resistant to head movements compared to EEG measurements [17]. Another alternative biometric technique that is increasing in popularity throughout design research is eye tracking. Eye-tracking technology calculates and analyses human gaze through integration of eye-movement data with visual field data. Measuring gaze duration and fixation related to design processes can provide insight into an individual's understanding of the representations and whether there are common strategies that designers may be using to address design problems [14,18–26].

Design neuroscience has been an emerging field in the past decade, and to date, few literature review studies on the topic have been published. Hu and Shepley [27] conducted a literature review of design neuroscience research; however, that study lacks a systematic approach, and the research included in the scope of that study was limited. Kim et al. [28] reviewed EEG-based design studies using a systematic literature review method, and an fMRI-based design studies review was conducted by Hay et al. [29]. Both of those studies only focused on a literature review of one particular biometric technique. To date, there has been a lack of comprehensive understanding informed by a systematic review approach about design studies that utilise biometric analysis. Therefore, this current study aims to review design neuroscience research throughout the past decade from 2013 to 2022 and illuminate the current body of knowledge relating to the use of biometric analysis to describe the underlying neural processes of design cognition as well as potential future research directions to further advance this area. The following Section 2 presents an outline of this systematic literature review research method. Section 3 presents results from the literature review, which leads to a discussion in Section 4 of distinguished biometric techniques and utilisation of biometric analysis to explore design thinking and creativity, design cognitive load and visual stimulation. Finally, the paper concludes with future research directions by which to further advance the field.

2. Research Method

2.1. Systematic Literature Review

This study adopts a systematic literature review methodology, that is a research method which identifies, synthesises and delineates boundaries of all existing knowledge within a given research domain by collecting and analysing data from relevant studies [30]. In this study, a four-step systematic literature review was conducted to analyse the most recent design studies using biometric analysis. The first step identifies the research topic, appropriate search keywords, and database for literature search. The next step is the database search and priority selection of articles, and it is followed by article screening, which includes reading and assessing each article to determine whether it is relevant and should be included. The final step is critical content analysis of the selected articles to gain a comprehensive understanding of the body of knowledge in the field. This replicable approach minimises potential biases among narrative reviews by being transparent in the collection and classification process according to specific eligibility criteria. The results of quantitative review articles include: (i) whom, where and when the research was published; (ii) the biometric measurement techniques utilised; (iii) the demographics of subjects examined; and (iv) the electrophysiological variables measured.

2.2. Selection of Database and Keywords

In this study, the Scopus database was selected for article retrieval, which is one of the most significant research publication databases. This is due to its wide coverage of articles, high integrity of its scholarly record, and its feasibility for conducting the queries necessary to identify relevant articles.

The keyword search was refined to the most commonly used biometric techniques including EEG, eye tracking, fMRI and fNIRS, as well as specific areas related to design cognition such as design thinking and design behaviour. In order to cover most of the articles related to design cognition, we also included some common subjects for design studies such as problem solving, design creativity, design ideation, etc. In the end, the following keywords were used for searching: (TITLE-ABS-KEY (electroencephalography OR eeg) OR TITLE-ABS-KEY ("eye-tracking" OR "eye tracking") OR TITLE-ABS-KEY ("functional magnetic resonance imaging" OR fmri) OR TITLE-ABS-KEY ("functional near infrared spectroscopy" OR fnirs) OR TITLE-ABS-KEY ("physiology measurement") AND TITLE-ABS-KEY ("expert and novice designers" OR "design problem solving" OR "design problem-solving" OR "problem space" OR "solution space" OR "design fixation" OR "design creativity" OR "concept design" OR "conceptual design" OR "design activities" OR "idea generation" OR "design neuroscience" OR "design neurocognition" OR "design protocol" OR "design process" OR "designers' behaviour" OR "design behaviour" OR "design thinking" OR "design cognition" OR "designers' thinking")). This original search generated a total of 460 potential articles.

2.3. Database Search and Priority Selection of Articles

During this phase, a database search of articles was conducted, keyed on the article's year, its type of document and source type, and the language of the document. The search was further refined to only include articles which were published within the most recent decade (2013–2022), which is the period in which the design neuroscience field was most actively academically studied. Filtering in relation to the type of document and source type was conducted to result only in publications which were journal articles, since journal articles typically provide deeper knowledge (compared to potentially less extensive publication types such as conference papers) and also typically pass through a more stringent peer review processes. Finally, non-English language articles were excluded, in accordance with the feasibility to conduct article reviews by the authors. The filter procedures are: (LIMIT-TO (PUBYEAR, 2022–2013)) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "j")). This refined search resulted in a total of 171 articles.

2.4. Screening of Articles

Initial screening of the selected articles from the last step was conducted based on relevance to the research topic of the information in each article's title. Articles that were not relevant to design related disciplines, such as articles related to medical research, were excluded. A total of 93 articles were selected by this step. This was followed by analysis of the full abstract by reading it to clarify the article's potential inclusion suitability. Articles were excluded at this point if the focus of the paper related to investigations into end-users' biometric responses or preferences or general creative ideation studies which were not relevant to design. Finally, a total of 44 articles were selected at this point for the subsequent full content analysis. Approximately 10% of the initial literature ultimately was selected for review; this percentage reflects the rigour of the selection criteria for identifying the most relevant articles for the review. The percentages of final articles divided by initial searched articles for some other systematic literature review papers are 14.7% [31], 10.2% [32], and 8.6% [33] respectively, which is similar with this study. Figure 1 illustrates the article retrieval and selection process.

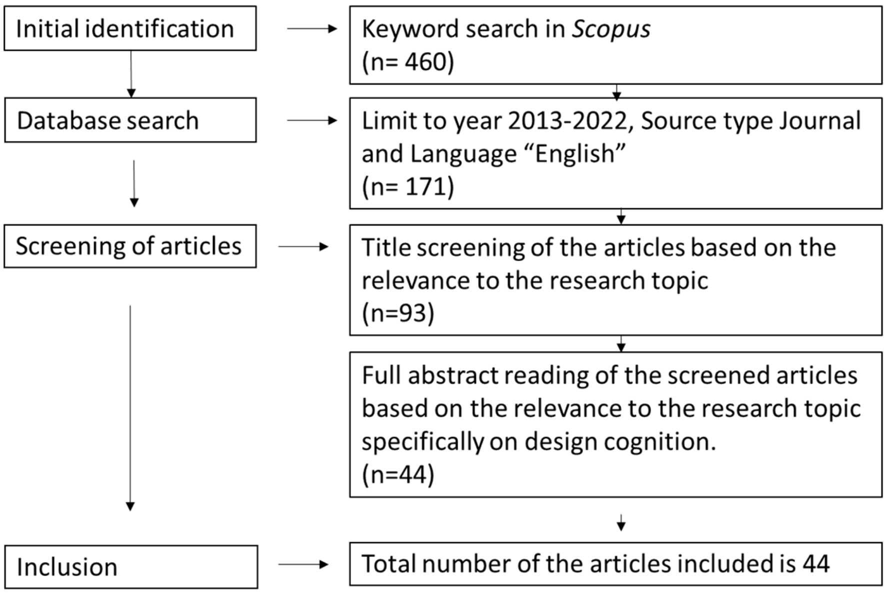

Figure 1. Article retrieval and selection process.

2.5. Content Analysis

In this step, content analysis of the selected 44 articles was conducted. Data were extracted as shown in Table 1, including basic publishing information (paper titles, author, journal, publication year), subject (focus area), and methodological techniques (biometric techniques explored and measurement parameters). Further categorisation of the retrieved articles then followed, via sub-categorisation into different themes of research, clustering them based on commonalities that correspond to research themes.

Table 1. Review articles on biometric analysis in design cognition.

Biometric Technique	Authors	Year	Region	Title	Source Title	Focus Area	Measurement Parameters
EEG	Yin, Y., Wang, P., Childs, P.R.N.	2022	UK	Understanding creativity process through electroencephalography measurement on creativity-related cognitive factors	Frontiers in neuroscience	Design creativity	Channels Fp1/Fp2/F7/F8/F3/F4 report signals on the frontal lobe, C3/C4/P3/P4 report signals on the parietal lobe, T3/T4/T5/T6 report signals on the temporal lobe and O1/O2 report signals on the occipital lobe.

Table 1. *Cont.*

Biometric Technique	Authors	Year	Region	Title	Source Title	Focus Area	Measurement Parameters
EEG	Hu, Y., Ouyang, J., Wang, H., Zhang, J., Liu, A., Min, X., Du, X.	2022	China	Design Meets Neuroscience: An Electroencephalogram Study of Design Thinking in Concept Generation Phase	Frontiers in Psychology	Cognitive effort, diverged thinking	Alpha (8–13 Hz), beta (13–30 Hz), theta (3.5 Hz-8), delta (0.5–3.5 Hz) and gamma (31–45 Hz) for task-related power.
	Vieira, S., Benedek, M., Gero, J., Li, S., Cascini, G.	2022	Italy	Brain activity in constrained and open design: The effect of gender on frequency bands	Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM	Gender differences on neurocognition of professional designers	High cut-off of 28 Hz to maintain only theta, alpha and beta frequency range.
	Kim, N., Chung, S., Kim, D.I.	2022	Korea	Exploring EEG-based Design Studies: A Systematic Review	Archives of Design Research	Review paper on EEG-based design studies	N/A
	Vieira, S., Benedek, M., Gero, J., Li, S., Cascini, G.	2022	Italy	Design spaces and EEG frequency band power in constrained and open design	International Journal of Design Creativity and Innovation	Comparison of the design process of mechanical engineers and industrial designers	Frequency bands theta, alpha 1 (7–10 Hz), alpha 2 (10–13 Hz), beta 1 (13–16 Hz), beta 2 (16–20 Hz), beta 3 (20–28 Hz). Band-pass filter of 3.5–28 Hz for theta to beta frequency range. Electrodes O1/2, P7/8, T7/8, FC5/6, F7/8, F3/4, AF3/4.
	Cao, J., Zhao, W., Guo, X.	2021	China	Utilizing EEG to Explore Design Fixation during Creative Idea Generation	Computational Intelligence and Neuroscience	Design fixation, idea generation	Data were filtered between 0.1 and 40 Hz, with principal component analysis to remove ocular artifacts.
	Wang, P., Wang, S., Peng, D., Chen, L., Wu, C., Wei, Z., Childs, P., Guo, Y., Li, L.	2020	UK	Neurocognition-inspired design with machine learning	Design Science		64 electrodes 10–20 system, notch filter 50 Hz.
	Zhao, M., Jia, W., Yang, D., Nguyen, P., Nguyen, T.A., Zeng, Y.	2020	Canada	A tEEG framework for studying designer's cognitive and affective states	Design Science	Loosely controlled experiment, complex design process	N/A
	Vieira S.; Gero J.S.; Delmoral J.; Gattol V.; Fernandes C.; Parente M.; Fernandes A.A.	2020	Italy	The neurophysiological activations of mechanical engineers and industrial designers while designing and problem solving	Design Science	Problem solving, basic design, open design	Filter excluding frequencies above 60 Hz.

Table 1. *Cont.*

Biometric Technique	Authors	Year	Region	Title	Source Title	Focus Area	Measurement Parameters
EEG	Nguyen, P., Nguyen, T.A., Zeng, Y.	2019	Canada	Segmentation of design protocol using EEG	Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM	Segmentation of design protocol, methodol-ogy paper	N/A
	Liang C., Chang C.-C., Liu Y.-C.	2019	China	Comparison of the cerebral activities exhibited by expert and novice visual communication designers during idea incubation	International Journal of Design Creativity and Innovation	Experts vs. novice, conceptual imagination	Channels Fp1 and Fp2 only. Filters cutting off 1–50 Hz.
	Hu, W.-L., Reid, T.	2018	US	The Effects of Designers Contextual Experience on the Ideation Process and Design Outcomes	Journal of Mechanical Design, Transactions of the ASME	Context-specific experience, mental state, creativity, evaluation of solutions	
	Liu, L., Li, Y., Xiong, Y., Cao, J., Yuan, P.	2018	China	An EEG study of the relationship between design problem statements and cognitive behaviors during conceptual design	Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM	Design problems, divergent thinking, convergent thinking, and mental workload	Band-pass filter 0.1 HZ–40 Hz.
	Nguyen, P., Nguyen, T.A., Zeng, Y.	2018	Canada	Empirical approaches to quantifying effort, fatigue and concentration in the conceptual design process: An EEG study	Research in Engineering Design	Concept design, effort, fatigue, and concentra-tion	Alpha (focus 8–15), Beta (16–31), Delta (<4), Theta (4–7), (Theta + alpha)/beta, Alpha/beta, (Theta +alpha)/(alpha + beta), Theta/beta.
	Liu, Y.-C., Chang, C.-C., Yang, Y.-H.S., Liang, C.	2018	China	Spontaneous analogising caused by text stimuli in design thinking: differences between higher- and lower-creativity groups	Cognitive Neurodynamics	Word stimuli, design thinking, high and low creativity groups of designers	Low-pass filter 50 Hz and high-pass filter 1 Hz. Whole-brain analyses.
	Liang, C., Liu, Y.-C.	2018	China	Effect of musical stimuli on design thinking: Differences between expert and student designers	Cogent Psychology	Musical stimulation, changes in design thinking	Low-pass filter 50 Hz and high-pass filter 1 Hz. Whole brain analyses.

Table 1. *Cont.*

Biometric Technique	Authors	Year	Region	Title	Source Title	Focus Area	Measurement Parameters
EEG	Liu, Q.	2018	China	Graphic creative design based on subconsciousness theory	NeuroQuantology	Unconsciousness of the brain, creation within design, creative thinking	Region of interest is frontal electrodes and T7. Frequency range 10–15 Hz.
	Liang, C., Lin, C.-T., Yao, S.-N., Chang, W.-S., Liu, Y.-C., Chen, S.-A.	2017	China	Visual attention and association: An electroencephalography study in expert designers	Design Studies	Visual attention, visual stimuli on design thinking	High-pass filter 1 Hz and transition band 0.2 Hz. Low-pass filter 50 Hz and transition band of 7 Hz. Whole-bran analyses.
	Yao S.-N., Lin C.-T., King J.-T., Liu Y.-C., Liang C.	2017	China	Learning in the visual association of novice and expert designers	Cognitive Systems Research	Expert vs. novice designers, visual association task	Frontal, prefrontal and cingulate cortices regions of interest. Los-pass filter 50 Hz and high-pass filter of 1 Hz. Mainly alpha and gamma band investigation.
	Sun, L., Xiang, W., Chai, C., Wang, C., Liu, Z.	2013	China	Impact of text on idea generation: An electroencephalography study	International Journal of Technology and Design Education	Idea generation, sketching, expert vs. novice	Theta band (theta1 = 4–6 Hz, theta2 6–8 Hz) and alpha band (alpha1 8–10 Hz, alpha2 10–13 Hz).
Eye-tracking	Zhu, M., Bao, D., Yu, Y., Shen, D., Yi, M.	2022	China	Differences in thinking flexibility between novices and experts based on eye tracking	PLoS ONE	Flexibility of design thinking, experts vs. novices	Fixation duration and saccade amplitudes.
	Fernberg, P., Tighe, E., Saxon, M., Spencer, C., Johnson, S., Stefanucci, J., Creem-Regehr, S., Chamberlain, B.	2022	US	Measuring perception of urban design elements in virtual environments using eye tracking: Benefits and challenges	Journal of Digital Landscape Architecture	VR-based design, geospatial and temporal patterns of spatial observations/inferences	Gaze tracking, total dwell time and total fixation count for areas of interest (buildings within VR environment).
	Härkki, T.	2022	Finland	Mobile gaze tracking and an extended linkography for collaborative sketching and designing	International Journal of Technology and Design Education	Design collaboration, convergent and divergent collaboration	Visit frequency, visit duration.
	Mehta, P., Malviya, M., McComb, C., Manogharan, G., Berdanier, C.G.P.	2020	US	Mining design heuristics for additive manufacturing via eye-tracking methods and hidden Markov modeling	Journal of Mechanical Design, Transactions of the ASME	Design behaviour	Fixation time.

Table 1. *Cont.*

Biometric Technique	Authors	Year	Region	Title	Source Title	Focus Area	Measurement Parameters
Eye-tracking	Nelius, T., Doellken, M., Zimmerer, C., Matthiesen, S.	2020	Germany	The impact of confirmation bias on reasoning and visual attention during analysis in engineering design: An eye tracking study	Design Studies	Problem-solving, disconfirming and misinterpreted information, visual attention	Eye-tracking glasses measuring fixation duration.
	Li, X., Jiang, Z., Guan, Y., Li, G., Wang, F.	2019	China	Fostering the transfer of empirical engineering knowledge under technological paradigm shift: An experimental study in conceptual design	Advanced Engineering Informatics	Empirical engineering knowledge, concept design	Fixation durations and counts.
	Self, J.A.	2019	Korea	Communication through design sketches: Implications for stakeholder interpretation during concept design	Design Studies	Design interpretations, conceptual design representations	Pupil dilation.
fMRI	Hay, L., Duffy, A.H.B., Gilbert, S.J., Grealy, M.A.	2022	UK	Functional magnetic resonance imaging (fMRI) in design studies: Methodological considerations, challenges, and recommendations	Design Studies	Review paper on fMRI-based design studies	N/A
	Tsai, Y.-P., Hung, S.-H., Huang, T.-R., Sullivan, W.C., Tang, S.-A., Chang, C.-Y.	2021	China	What part of the brain is involved in graphic design thinking in landscape architecture?	PLoS ONE		20-channel head coil used to take images. 45 EPI slices were sampled in bottom–up, interleaved order.
	Shen, T., Gao, C.	2020	China	Sustainability in community building: Framing design thinking using a complex adaptive systems perspective	Sustainability (Switzerland)	Design thinking, complex adaptive systems	oxy-Hb in the participants' cerebral cortices.
	Hay, L., Duffy, A.H.B., Gilbert, S.J., Lyall, L., Campbell, G., Coyle, D., Grealy, M.A.	2019	UK	The neural correlates of ideation in product design engineering practitioners	Design Science	Creative ideation	Blood oxygen level dependent (BOLD) signal, various brain regions.

Table 1. *Cont.*

Biometric Technique		Authors	Year	Region	Title	Source Title	Focus Area	Measurement Parameters
fMRI		Goucher-Lambert, K., Moss, J., Cagan, J.	2019	US	A neuroimaging investigation of design ideation with and without inspirational stimuli—understanding the meaning of near and far stimuli	Design Studies	Inspirational stimuli, design ideation	Cluster size, location, in various brain regions.
		Lazar L.	2018	India	The cognitive neuroscience of design creativity	Journal of Experimental Neuroscience	Design creativity, "ill-structured" tasks	Various brain regions including PFC, parietal cortex (PC), the anterior, cingulate cortex (ACC).
fNIRS		Hu, M., Shealy, T., Milovanovic, J., Gero, J.	2022	US	Neurocognitive feedback: A prospective approach to sustain idea generation during design brainstorming	International Journal of Design Creativity and Innovation	Design ideation, brainstorming	Oxygenated blood (Oxy-Hb) in the prefrontal cortex (PFC).
		Milovanovic, J., Hu, M., Shealy, T., Gero, J.	2021	US	Characterization of concept generation for engineering design through temporal brain network analysis	Design Studies	Divergent and convergent thinking, design concept generation technique	Central nodes.
		Hu, M., Shealy, T., Milovanovic, J.	2021	US	Cognitive differences among first-year and senior engineering students when generating design solutions with and without additional dimensions of sustainability	Design Science	Concept generation, sustainable design	Oxy-Hb using fNIRS in the PFC.
		Shealy, T., Gero, J., Hu, M., Milovanovic, J.	2020	US	Concept generation techniques change patterns of brain activation during engineering design	Design Science	Concept generation techniques, divergent/convergent thinking, ill-defined problem solving	Sampling frequency of 4.44 Hz. change in participants' oxygenated haemoglobin. Channels over prefrontal cortex.
Combined method	Reviewed EEG, MRI, NIRS, PET	Hu, L., Shepley, M.M.	2022	US	Design meets neuroscience: A preliminary review of design research using neuroscience tools	Journal of Interior Design	Review paper on design and neuroscience	N/A

Table 1. *Cont.*

Biometric Technique		Authors	Year	Region	Title	Source Title	Focus Area	Measurement Parameters
Combined method	ECG, EEG	Tang, Z., Xia, D., Li, X., Wang, X., Ying, J., Yang, H.	2022	China	Evaluation of the effect of music on idea generation using electrocardiography and electroencephalography signals	International Journal of Technology and Design Education	Creative idea generation, music impact	Heart rate, theta (4–8 Hz), alpha1 (8–10 Hz), and alpha2 (10–12 Hz) frequency bands.
	EEG, ECG, respiration rate, and GSR	Jia, W., Zeng, Y.	2021	Canada	EEG signals respond differently to idea generation, idea evolution and evaluation in a loosely controlled creativity experiment	Scientific Reports	Creative idea generation and evaluation	EEG filtered to 1–30 Hz bends for power analysis and microstate analysis. Whole-brain analysis.
	EEG, HRV with ECG, eye-tracking, facial action coding system, fMRI	Gero, J.S., Milovanovic, J.	2020	US	A framework for studying design thinking through measuring designers' minds, bodies and brains	Design Science	Design thinking, design analysis and evaluation	N/A
	EEG, skin conductance	Nguyen, T.A., Zeng, Y.	2017	Canada	Effects of stress and effort on self-rated reports in experimental study of design activities	Journal of Intelligent Manufacturing	Mental stress and mental effort during design activities	beta2 power.
	ECG, EEG, EMG, pulse oximetry, blood pressure, body temperature, galvanic skin response measures and others.	Balters S.; Steinert M.	2015	Norway	Capturing emotion reactivity through physiology measurement as a foundation for affective engineering in engineering design science and engineering practices	Journal of Intelligent Manufacturing	Review on using physiology sensors to capture human emotion reactivity in a products or systems engineering context	N/A
	EEG, HRV	Nguyen, T.A., Zeng, Y.	2014	Canada	A physiological study of relationship between designer's mental effort and mental stress during conceptual design	CAD: Computer-Aided Design	Designers interaction with design tools and mental effort	EEG data high-pass filtered 0.3 Hz and low-pass filtered at 40 Hz. Notch filtered at 60 Hz. HRV data converted using HRVAS software at each 0.5 s using wavelet transform.

3. Results

3.1. Publication Trends in Design Cognition Based on Biometric Analysis

This study reviewed publications within the most recent decade (2013–2022), during which time design neuroscience as an emerging area has become increasingly studied. Figure 1 shows the annual publication trend of articles for biometric analysis in design cognition. From Figure 1, we can see that there is an increasing trend of publications in this area since 2017. The amount of publications has significantly increased compared to previous years, which is potentially because of the advancements seen in biometric analysis techniques, including better convenience and ease of setup/use of necessary biometric measurement equipment. Notably between 2010 and 2013, there were several key commercial EEG products released onto the consumer market, such as NeuroSky's MindWave (https://store.neurosky.com/pages/mindwave, accessed on 27 February 2023), which popularised and contributed to the effective use of such measurement tools at relatively minimal cost, and broader widespread adoption. Additionally, the increasing availability of open-source API tools for such consumer technologies in that period also accelerated the adoption and various applications of such EEG products. Since traditional research methods within the design cognition field such as interviews, observations, and protocol analysis had mostly been utilised for decades with few innovations, the field had a clear potential for more optimal development via the integration of new research methodologies; in such a manner, the mysteries of the design process can be better illuminated based on the light of objective evidence. Such contributing factors culminated in the boom over the past five years of design cognition studies utilising biometric analysis, as seen in Figure 2. Among this study's included papers, there was only a single paper included from each calendar year from 2013–2015, and zero papers from calendar year 2016, which is indicative of the early stages of this emerging field. By contrast, 2017 saw an increase of studies in the design neuroscience field, and in the past 5 years from 2018 onwards we have witnessed a relative research boom in this area.

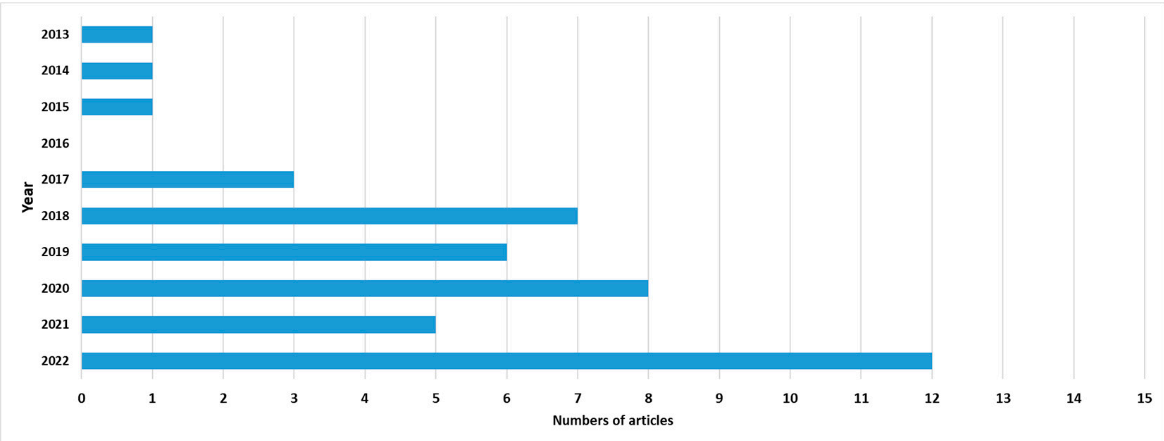

Figure 2. Annual publication trend of articles for biometric analysis in design cognition.

3.2. Content Analysis of Review Articles

Table 1 categorises the 44 articles that have been reviewed. Figure 3 shows the biometric measurements techniques adopted in those articles. From the figure, we can see that the most utilised biometric technique is EEG, which is used in 27 articles. That is followed by eye-tracking and fMRI, which both have seven articles. fNIRS has four articles, and some combined methods (including other techniques such as facial action coding system, HRV and others) were utilised in seven articles.

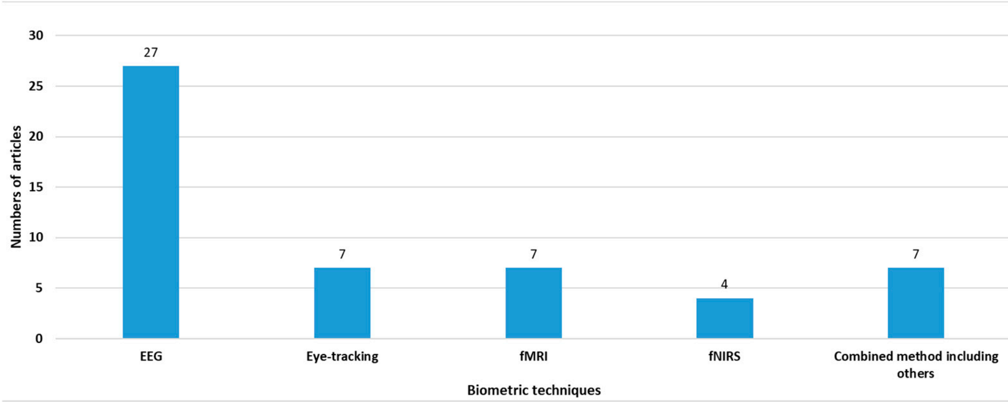

Figure 3. Biometric measurements techniques adoption.

Figure 4 illustrates the number of included publications originating from researchers in different regions based on first author's affiliation. The data reveal that the top regions of origin with the highest number of included publications were China, the US, and Canada, with 15, 10 and 6, respectively. This study has also identified that during recent years, a few groups of key research teams have been particularly active and responsible for an overly significant proportion of recent publications within the design neuroscience field. For example, six articles were co-authored by the research team at National Taiwan University (co-authored with Liu, Y.-C and/or Liang C), and seven articles were co-authored by Gero et al.

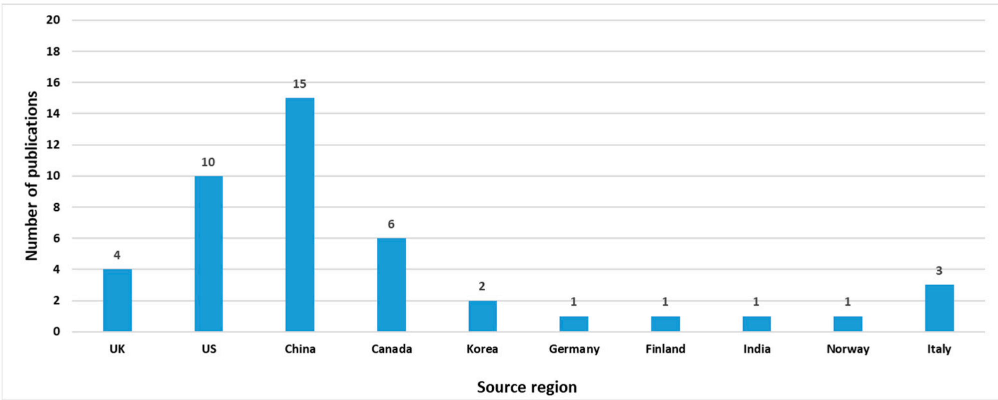

Figure 4. International affiliation of included publications.

From Table 1, we can see that the most articles (7) were published in *Design Science*, which is followed by *Design Studies* (6) and *AIEDAM: Artificial Intelligence for Engineering Design, Analysis and Manufacturing* (3), which represent the major journals in design cognition. The focused areas have been around the typical common areas of design cognition studies, such as design thinking strategies, design creativity, and problem solving; additional areas such as cognitive load and visual attention were also studied extensively. This is due to the nature of biometric measurement such as eye-tracking being particularly practical and suitable to explore those aforementioned aspects of designers' behaviour. The main biometric measurement parameters include frequency bands using EEG, fixation-related parameters and pupil size using eye-tracking, blood oxygen level-dependent signals in relation to different brain regions using fMRI, and oxygenated blood using fNIRS, amongst others. The results of this review are discussed in further detail in Section 4.

4. Discussion

Biometric analysis has been increasingly applied to design cognition research during the past decade. The application of biometric measurements reveals designers' biometric responses during their design process and enables a more in-depth understanding of design processes. This section discusses the principal biometric techniques and measurements as well as current design cognition studies that utilise biometric analysis.

4.1. Biometric Techniques and Measurements

4.1.1. EEG and Associated Measurements

EEG tools are used for measuring and analysing brain activities associated with thinking and behaviour based on the human brain's electrical signal frequencies [7]. EEG technologies have been used in design studies to measure designers' brain waves while they perform their design activities to correlate designers' biometric responses to different aspects within their design processes. Such an approach facilitates an in-depth investigation and understanding of the cognitive processes of designers. For example, Vieira et al. [34] identified gender differences in the neurocognition of professional designers based on the theta, alpha and beta band within occipital and visual areas as well as the prefrontal cortex (PFC), which is affected by gender. Nguyen et al. [35] presented a methodology article discussing the utilisation of EEG to conduct a design protocol segmentation method for design studies, which is a method that is an advancement compared to a traditional protocol segmentation method using protocol analysis. The benefits of using EEG include that it is relatively affordable, and due to the non-invasive nature, EEG is a safe measuring tool which will not harm participants. EEG also allows head movement and so it can simulate a natural design environment. The downsides of EEG technology include its low spatial resolution.

Principal measurements for EEGs include the frequency bands alpha, beta, theta, delta and gamma, and their relationship to various aspects of design thinking. For instance, researchers have identified that creative thinking is associated with theta (4–8 Hz), alpha (8–13 Hz), and beta (13–30 Hz) bands [36]. EEG technology can also identify activity in different brain areas, which can be associated with various aspects of design thinking. For example, EEG analysis has shown that brain activity in the anteriofrontal area is believed to be associated with divergent and convergent thinking, while the parietotemporal area is associated with creative ideation [27]. The prefrontal cortex (PFC) is associated with planning complex cognitive behaviours, such as design idea generation [37].

4.1.2. Eye-Tracking and Associated Measurements

Eye-tracking systems measure eye position, eye movement and pupil size to define the direction and duration of a person's gaze [38]. Since the 1970s, there has been an increase in the use of eye-tracking applications, which is often driven by research in advertising, marketing, psychology, neuroscience, and user interface design. The usage of this widely applied technology is constantly advancing, including encompassing new analytical methods, for example, the recording of visual sequences known as gaze paths [39]. Recent years have also witnessed its application for design cognition studies. For instance, Zhu et al. [40] studied the eye movement of design experts and design novices during their design processes, and their results suggested that experts display higher fixation durations and fixation numbers during their thinking activities and that experts consider information in a more balanced manner compared to novices. Mehta et al. [41] used eye-tracking to study engineering graduate students' design behaviour; their results suggested there is a smoother transition between design states for high-performing designers than for lower-performing ones. The availability of visual attention simulation software can also emulate the predicted eye-tracking results for typical viewers for a given static image [42] and can also thus be utilised as an increasingly useful supplementary tool for eye-tracking studies.

Principal measurements of eye-tracking data relate to eye movement, eye position and pupil size. Eye movement is often analysed based on eye fixation parameters within a predefined area of interest (AOI). Within an AOI, typical measurements are Average Time to First View, Average Time Viewed, Average Number of Fixations, Number of Revisitors, and Average Revisits [43]. Average Time to First View measures on average the time that elapses before participants first fixate on an active AOI. Average Time Viewed is how long on average participants view within an active AOI. Average Fixations measures the average number of times that a participant typically will fixate on an AOI. The Average Revisits measures the number of visits within an active AOI. Number of Revisitors means how many participants revisit an AOI, and the definition of Average Revisits is an interval of time between a participant's first fixation on the active AOI and the conclusion of a participant's final fixation on that same AOI (if there have been no fixations outside of the AOI during that time).

4.1.3. fMRI and Associated Measurements

fMRI records brain activity based on changes in cerebral blood oxygenation [29]. The benefit of using fMRI is that it is effective at locating the brain regions involved in cognition tasks due to fMRI's high spatial resolution [13]. However, the technology is relatively expensive. fMRI has been applied in design cognition research in recent years in relation to ideation and activities in different brain region. For instance, Hay et al. [44] used fMRI to explore the ideation of product engineering design processes, with results suggesting that ideation is associated with greater activity in the left cingulate gyrus. Shen and Gao [45] studied the design process of designers via fMRI based on the Agent–Interaction–Adaptation design (AIA) thinking framework, with results proving that the AIA framework facilitates understanding of a typical designer's extended idea space, ideas quality, and their brain activations. In design cognition research, fMRI measures blood oxygen level in various brain regions, which are associated with design activities, such as in the PFC, parietal cortex (PC), anterior and cingulate cortex (ACC) regions.

4.1.4. fNIRS and Associated Measurements

fNIRS is the use of a near-infrared light emitted into a human cortex with the change in light absorption indicating changes in oxygenated blood [46]. Being similar to fMRI technology, fNIRS started to be applied within design cognition research work due to its benefits including portability, affordability and greater tolerance for motion; however, the downside of fNIRS is its relatively poor spatial resolution and limited temporal resolution [47]. The application of fNIRS on design cognition research has been focused on exploring design thinking strategies. For example, Hu et al. [48] used fNRIS and studied designers' neurocognition, with results suggesting that designers who received neurocognitive feedback demonstrated positive performance in relation to idea generation. fNIRS measurements can encompass oxygenated blood in various brain regions such as the PFC, which is highly related to creative design activities [48].

4.1.5. Other Biometric Techniques

Other biometric techniques include physiological measurements such as heart rate, facial action coding system, measurements of blood pressure, respiration, galvanic skin response and body temperature. Such physiological measurements can "describe design as an embodied activity that considers the designer's mind, body and brain" [20], therefore revealing the cognitive behaviour of designers from multiple perspectives. Table 2 summarises the advantages and disadvantages of principal biometric techniques.

Table 2. Advantages and disadvantages of principal biometric techniques.

Biometric Techniques	Advantages	Disadvantages
EEG	Relatively affordable; non-invasive; allows head movement.	Low spatial resolution.
Eye-tracking	Relatively affordable; non-invasive; diverse applicability such as gaze tracking, fixation, pupil size etc., mobile eye-tracking device allows physical movement.	Data limited to eye tracking only.
fMRI	Effective at locating the brain regions involved in cognition tasks; high spatial resolution.	Relatively cost prohibitive.
fNIRS	Portability; affordability and greater tolerance for motion.	Relatively poor spatial resolution; limited temporal resolution

4.2. Using Biometric Analysis to Explore Design Thinking and Creativity

Design thinking combines problem-finding and problem-solving behaviours [49]. Asimow (1962) suggests that the design process follows a spiralling path of analysis, synthesis and evaluation. Some scholars defined two types of design thinking, which are convergent thinking and divergent thinking [50,51]. Traditional design studies apply methods of observation, interviews and protocol analysis [52,53]. In recent years, with advancements in neurophysiology, biometric measures of eye movement, EEG, and other technologies have all been gradually introduced and effectively utilised to demystify design thinking.

4.2.1. Design Problem Solving

Design is an activity that involves the pursuit of design solutions often by needing to reframe or redefining the initial design problems that have been presented [54,55]. Prior studies have demonstrated that expert design processes also require close interplay between representations of problems and solutions [56]. Thus, rather than perceiving a design process to simply be a progressive refinement, instead, design can be understood in terms of cognitive effort shifts occurring between a designer's consideration of the problems and solutions [57,58]. Previous studies have explored how designers shift from design problem space to solution space, using protocol analysis method to identify the frequency and patterns of the co-evolutionary design process [57,59].

Recent studies using biometric analysis have further revealed the design activities of designers and their physiological responses during their design problem-solving processes, which are associated with different areas of their brain activities. For instance, studies suggest that when formulating and analysing design problems, there is less cognitive effort required based on the activation in the prefrontal cortex detected via fNIRS [17]. Liu et al. [60] demonstrated that results in specific EEG bands correlate to design activities, such as problem solving and evaluation. Statistically significantly different behaviours were also identified during elementary design tasks within the left frontal and occipital areas associated with idea generation and problem solving [1]. Using fMRI, Goucher-Lambert and McComb [15] identified that designers tend to transfer between various key states during open-ended design problems, and there are differences of occupancy of those key states between high-performance and low-performance designers.

EEG has also been utilised for comparing the problem-solving of designers from different disciplines. For example, Vieira et al. [13] compared the neurocognition of architects and mechanical engineers, using temporal resolution of EEG, and their results suggest domain differences in power when comparing problem-solving tasks and open design tasks in terms of temporal resolution and transformed power. The same research team, Vieira et al. [11], used EEG to measure the neurophysiological activations of industrial designers and mechanical engineers during their designing and problem-solving tasks, and they suggested that significant differences in activation may be present when measuring problem-solving tasks compared against open design tasks.

Eye tracking has also been utilised in design problem-solving studies: for example, Härkki [61] explored design problem solving during collaboration using eye tracking and demonstrated an effective method using gaze data and linkography to explore design problem solving. Nelius et al. [22] explored situations of misinterpreted information, where low visual attention could contribute to confirmation bias within a problem-solving space, using eye tracking and protocol analysis.

4.2.2. Design Thinking Strategies—Divergent and Convergent Thinking

Design researchers have studied the impact of various design thinking strategies on design, such as convergent and divergent thinking [62]. Generally, divergent thinking seeks multiple possible solutions to problems, while convergent thinking assumes that a problem has a single solution [63]. Convergent thinking has a problem-solving focus on existing ideas, while divergent thinking is more associated with creative or emergent new ideas [18]. Biometric measurements have been applied to explore design thinking strategies such as divergent and convergent thinking in relation to different types of design tasks. For example, EEG-based results identified a relationship between the design process and different parts of a designer's brain activities in relation to designers' divergent thinking, convergent thinking and mental workload; specifically, open-ended statements assist designers to generate fresh ideas by stimulating their divergent thinking, while decision making and constrained tasks have better performance in convergent thinking [9]. Using protocol analysis and EEG analysis, Hu et al. [64] found that task-related synchronisation and divergent thinking are in a dominant position, and the parietooccipital area differs significantly from other areas during design due to the visual function and cognitive control within this area. Colombo et al. [18] validated methodological experimental protocols for divergent and convergent thinking tasks during design, using EEG and eye-tracking, suggesting that idea generation differs between engineers and designers.

Brain activities vary when different design concept generation techniques are used. For instance, based on fNIRS analysis, studies suggest greater demands for brainstorming and morphological analysis in the prefrontal cortex compared to TRIZ. Meanwhile, activations in the right DLPFC and VLPFC during brainstorming and morphological analysis can be associated with divergent thinking and the creatively emergent solving of unclearly defined problems. In addition, TRIZ shows greater activation in the left DLPFC associated with convergent and judgemental thinking [65]. In another similar study, Milovanovic et al. [66] conducted an fNIRS analysis to explore designers' physiological responses in relation to design concept generation techniques of brainstorming, TRIZ and morphological analysis, and their findings suggest that the medial PFC has a consistent centrality when utilising all three of the aforementioned analytical methods; that is indicative of a possible tendency during concept generation towards cognitive empathy and memory association.

4.2.3. Design Creativity and Design Fixation

Researchers usually approach creativity in design from four perspectives: creative processes, creative outcomes, creative individuals, and the actual interactions between creative individuals and the design context/environment [67]. Creative ideas are expected to be novel, appropriate [68], surprising or efficient [69]. Creative processes do not guarantee a creative outcome [70]. The exploration of creative processes has grown in strength over time, as its results have been shown to be both replicable and generalisable [71,72].

In the recent decade, EEG technology has been applied to investigate designers' creative design process. For example, using EEG analysis, Rominger et al. [73] found that creative ideation was associated with a strong desynchronization of upper alpha power and occipital sites. Another study found creativity to be related to the frontal lobe area of the brain that is typically associated with unconscious processes [74], while yet another study on creative activity using EEG suggested that idea evolution may place lower demands on attention compared with other modes of thinking and may therefore be associated with unconscious internal attention processes [75]. Furthermore, during the process of ideation, contextual personal experiences can have detrimental effects on the mental states typically associated with creativity, which carries over into reduced novelty of the resulting proposed solutions [10].

Researchers have utilised biometric measurement to study the impact of various types of stimuli on design creativity. For instance, various brain activities and differences caused by distinct word stimuli were found between high and low creativity groups of designers based on EEG measurement [76]. Similarly, an EEG-utilising study suggested that the involvement of text in idea generation had an positive impact on design creativity and idea generation [77]. Goucher-Lambert et al. [78] used fMRI to explore the differences between ideating with inspirational stimuli compared to ideating without such stimuli, and their results showed inspirational stimuli improved the fluency of idea generation. Furthermore, using EEG and ECG measurements, Tang et al. [79] found that a higher quantity but lower quality of design ideas was produced in positive music conditions, and alpha brain activity was associated with creative idea generation, while theta brain activity varied based on different music conditions.

Design fixation is usually considered as a counterproductive factor for design creativity [80]. A definition of design fixation is "a blind adherence to a set of ideas or concepts limiting the output of conceptual design" [81]. Utilising biometric analysis methods, researchers have investigated designers' brain activities when designing from various perspectives to further explore design fixation. For example, Cao et al. [4] utilised EEG to look for neural activity variability in different degrees of fixation of designers during their creative idea generation process and found that designers with low design fixation showed greater alpha synchronization in their frontal, parietotemporal, and occipital regions during their creative idea generation; that result is indicative of designers with higher fixation having lower solution flexibility. Utilising eye-tracking analysis, Smith et al. [25] identified major discrepancies in what was recalled by designers as the features they had seen compared to the features that were actually seen and fixated on by the designers based on eye-tracking measurements. Another study conducted by Hu et al. [82] using fNRIS explored sustainable design, comparing junior and senior engineering students, and the results suggested that senior students had more potential for design fixation tendencies.

4.3. Using Biometric Analysis to Explore Design Cognitive Load and Visual Stimulation

4.3.1. Measuring Design Cognitive Load Using Biometric Analysis

Cognitive load is an empirical evidence-based measurement derived via psychology and physiology experiments during cognitive activities [83,84], which is defined as the total amount of mental effort involved in a task. Direct correlations between cognitive load and pupillary response have been discovered by utilising eye-tracking technology; for example, Hess and Polt [85] stated that while simple multiplication problems are being solved, corresponding changes in pupil size may be related to some kind of associated mental activity. Granholm et al. [84] suggested that increased pupil dilation may be associated with higher cognitive load. Hence, pupil diameter is a viable measurement of cognitive processes and mental workloads [86], which means that such internal processes can be empirically tested to assess whether different visual representations of architectural spaces might lead to differences in typical associated cognitive loads. Differences in cognitive load are also implied indicators of differences in the subject's responses. Furthermore, studies also indicate statistically significant cognitive load changes during a variety of changes to architectural spaces [87].

Nguyen's team conducted a series of studies using EEG technology to explore designers' mental effort during design activities. For instance, Nguyen and Zeng [88] investigated both designers' mental stress and mental effort using EEG measurement, body movement, and heart rate, and their results suggested that during conceptual design, a designer's mental effort was observed to be at its lowest during high stress levels. However, although residual lasting stress continued to be observed after the design had been completed, the designers' mental effort was not impacted by such residual stress [89]. Another of their EEG studies indicated that conceptual design processes are affected by a designer's concentration level, effort level, and fatigue level [90].

4.3.2. Visual Attention in Relation to Design Representation Studies Based on Biometric Analysis

Design representation is an increasingly important factor in both design communication and design thinking [91,92]. With the development and widespread adoption of computational modelling, digital design representations now dominate most design processes, assisting designers to "off-load" their cognitive load and also to offer the increased flexibility of interacting with external/virtual representations [55]. Designers typically focus on visual stimuli and look for visual references when designing a product; therefore, they tend to apply such stimuli when designing solutions, particularly during conceptualization [3]. Designers and other stakeholder including managers and engineers communicate and interpret design intentions via design representations differently [24,93]. Liang et al. [94] investigated areas of cerebral activity in relation to image-based visual stimulation experiments and performed comparisons of the EEG results for both beginner and expert designers who engaged in conceptual imagination tasks; their findings showed that designers engaging in virtual activities experienced stimulation in their PFC and temporal cortex, and the spectral power of expert designers was higher than that seen in beginner designers (except for the left temporal cortex), and significant differences were found in the alpha and theta bands in PFC between beginner and expert designers.

Guan et al. [95] investigated potential correlations between designers' design thinking processes and their visual attention, and they assessed the reliability of the "think-aloud" research method via experiments in which a designer's eye movements were recorded via eye tracking while they were speaking aloud, and their findings indicated that additional levels of complexity do not reduce the robustness and validity of the "think-aloud" research method. Liang et al. [96] explored both the visual association and visual attention of designers via EEG, and their findings showed that the frontoparietal brain region becomes especially activated when designers were engaged in visual attention tasks, while the prefrontal, frontocentral and parietooccipital regions were active during visual association tasks.

5. Conclusions

Biometric approaches to cognitive design studies can provide empirical evidence to enhance and complement current knowledge about design cognition. Using biometric measurements of designers during their design process, more objective data related to physiological responses can be obtained. Analysis and correlation can then be conducted to explore potential relationships between designers' physiological responses and the specific design research focus. In contrast to such biometric approaches, traditional research methods such as protocol analysis rely heavily on a designer's own accounts of their thoughts and actions, which may be distorted through a more subjective lens. What designers say and (sometimes) think they are doing while designing is not necessarily an accurate reflection of what is occurring. On the other hand, protocol studies are traditionally well established in cognitive design research, and their results have been validated, debated, refined and documented over significant bodies of work. They also provide an important theoretical foundation for benchmarking and contextualising new findings. Having a variety of different research tools allows design scholars to select the most suitable tools for their intended research problem, which remains more insightful than promoting a single approach for all problems.

This study reviewed biometric analyses in design cognition studies during the past decade, and based on this review, the results suggest that there has been an increasing trend of publications in this field. EEG technology has been the most utilised biometric technique in design studies to date, and most design studies have investigated common study areas such as design problem solving, design creativity, design thinking strategies, cognitive load and visual attention. Explored topics have included comparisons between design experts and beginners, comparisons of various design techniques/concepts, and comparisons of designers from different disciplines. The application of biometric analysis within the design cognition field has provided a deeper understanding of its theories and main aspects of design studies by correlating designers' physiological responses with their design process. This can particularly reveal new perspectives about existing design cognition theories, for instance, specific brain activities related to specific design phases, techniques for creativity, design events, a range of stimuli, etc. Design neurocognition is still an emerging field; thus, there are many research areas within design cognition that can be more deeply explored using biometric analysis techniques. Therefore, the following future research directions would be prudent.

First of all, further investigation of designers' cognitive behaviours in various digital design environments is suggested, since design media has been known to affect designers' design processes [97]. In light of the accelerating adoption of digital design tools by designers, academics have suggested that such digital design environments could have unknown or unintended impacts upon designers' thinking and behaviour [59,98,99]. Digital design media may advance designers' thinking within certain limitations, and so the features and restrictions of digital design environments have an important influence [100]. Most current design neuroscience research has studied designers' behaviour in a traditional sketching environment [24,61]. There is a lack of current studies exploring designers' behaviour in various digital design environments, especially of emerging digital technologies being applied in the field such as parametric design and virtual/immersive design environments.

Secondly, further research is needed to improve practical applications for the findings of recent design studies which used biometric analysis. One of the challenges of traditional design studies is in looking for practical applications for findings, for example translating the findings into design guidelines/recommendations for improving design practices or design education [101]. Since utilising biometric analysis, designers' physiological responses can be revealed and correlated with their design activities, therefore providing a more in-depth understanding of design. This provides opportunities for providing empirical evidence to better inform design training; for example, there may be benefits to aiming to trigger particular brain activities to optimise certain design processes. Thus, it is advisable to increasingly apply findings to such design studies to improving design practices or design education.

Finally, further ongoing development of biometric technologies and techniques applicable to design research would be prudent, as current biometric technologies and techniques still have their previously mentioned limitations. In the future, there will eventually be a need for technological advancements to enable further integrated measurements of brain activities from multiple simultaneous perspectives, potentially utilising multiple integrated technologies to overcome the current limitations and shortcomings of any single technological biometric approach, from the perspective of applicability to design research.

The selected systematic literature review research method has some unavoidable limitations; for example, although the single database selection of *Scopus* includes the most relevant and significant publications, nevertheless, there are some significant papers inevitably excluded from such a database, and the specific selected scope of English language journal articles would have led to the exclusion of some other types of sources such as conference papers and papers published in other languages (albeit the aforementioned scope selection is justifiable because it ensures the inclusion of the most significant articles within a reasonable numbers of publications). Future studies could be extended to encompass broader databases and literature sources, including recent studies published as conference papers; moreover, additional biometric techniques such as physiological measurements could be included to facilitate deeper understanding. The results of this study contribute to a more comprehensive understanding of existing knowledge about the application of biometric analysis for design cognition studies as well as of potential future research directions, and it is beneficial for future design research and education, and it can lead to the further practical application of design cognition studies.

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