Characterizing the EEG Features of Inspiring Designers with Functional Terms

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Abstract. This paper constructed an inspiring database containing functional terms, which was taken as the source of external stimuli provided to designers. We obtained EEG of two groups of designers based on design experiment. One group is provided with closely related functional terms, while another group is provided without stimuli. After processing these EEG, we found that there are different characteristics in the EEG for the two groups of designers. Our experimental results provide a basis for the study of design thinking using EEG.

Keywords: EEG features · Inspiring designer · Functional term

1 Introduction

The ability of creative design lies in the ability to create novel design solutions [1]. The design solutions are derived from designers' experience and knowledge [2], which also limit designers' space for generating novel design solutions [3]. One common phenomenon is that designers are often fixed on existing experience [4]. Therefore, using external stimuli to inspire designers is one of the important methods to assist concept design.

The key to inspire design is to reveal the influence mechanism of external stimuli on design thinking [5], and to provide designers with appropriate external stimuli based on this mechanism. To this end, many scholars have explored the impact of external stimuli on innovative design through cognitive experiments. Miller [6] proved that designers exposed to physical examples would produce ideas that were less novel and less functionally focused than those who were exposed to the 2D representation. Sarkar [7] provided designers with video/animation and audio, text, explanation, and other stimuli respectively, and the results showed that the types of stimuli have major influence on the number and quality of the generated ideas. Among diverse types of stimuli, texts were proved to be capable of inspiring designers. Because of the characteristics of being ubiquitous and easy to be measured, texts were widely used in the research community. For instance, Miller [1] showed that text stimuli yield ideas that would receive higher originality grades compared to a no stimulus condition, but practicality was not affected. Linsey [8] found that the addition of a function structure or more general functions (stated as active verbs), to the sketch-based concept de-sign improved designers' ability of finding novel solutions.

M. Kurosu (Ed.): HCI 2018, LNCS 10901, pp. 371–381, 2018.
https://doi.org/10.1007/978-3-319-91238-7_30

However, the unknown internal mechanism that governing how functional terms influence design thinking makes the above results difficult to be interpreted. At present, scholars have come up with the methods of think aloud [9] and sketching behavior [10] to indirectly obtain the state of design thinking, but these methods are more or less influenced by subjective factors. Therefore, it is very valuable to study the objective description method of design thinking. Recently, physiological signals such as eye-tracking, galvanic skin response (GSR), electrocardiograms (ECG), and electroencephalograms (EEG) have been used by design researchers to describe the conceptual design process. Among them, the process of exploring design thinking based on EEG is an important theoretical research direction of design science [11]. The biological basis of brain activity is an electrochemical process, and EEG is a charge signal recorded by electrodes placed in various regions of the brain [12]. We can extract valuable information from the EEG to describe the conceptual design process, and then explore the impact of external stimuli on conceptual design.

The goal of this work is to use EEG to describe the design thinking. In order to achieve this goal, Sect. 2.1 constructed an inspiring database represented by functional terms, which was taken as the source of external stimuli provided to the designers. Then we constructed the FCM based on the database, by which it could export functional terms that are closely related to the design problem. Section 2.2 identified the experiment scheme and process. Section 3 calculated the sample entropy of EEG data that could represent the complexity, and then analyzed them qualitatively and quantitatively. Section 4 discussed the analysis results and Sect. 5 summarized the experiment results, which provide theoretical basis for how to assist designers in product innovation design in information provision.

2 Method

2.1 Obtain External Information

2.1.1 Build Functional Database

In conceptual design, functional modeling provides a direct method for understanding and representing an overall product function without reliance on physical structure [13]. In practice, to achieve repeatable and meaningful results from functional modeling, a right size of functional inspiring database is in need. Hirtz and Stone [14] built RFB, whose functional part consists of 8 major categories and 22 minor categories. However, this database is not big enough to cover all product features. Murphy constructs a set of functional terms through natural language processing [15]. They extracted 1,700 function terms from a large number of patents and established a large-scale functional database. With the enlargement of the size of a functional database, the designers will describe the same design concept in different ways and ambiguities may arise.

In order to solve this problem, we filtered and reorganized the above two to construct a proper functional database. We used RFB as a basis for the similarity of function terms calculated by WordNet as a screening indicator. Then, the filtered function terms were reorganized with RFB to obtain a functional database to inspire designers. The whole process contains the following 3 steps (Fig. 1).

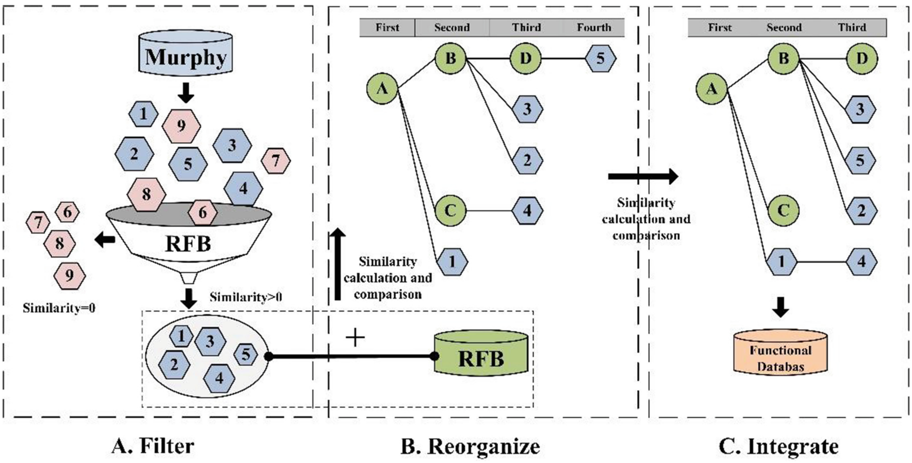

Fig. 1. The process of building Functional Database.

1. **Filter**: The terms in RFB and Murphy are all three-levels and share the same first level. Calculate the similarity between Murphy's second level, third level terms and the terms in RFB. Remove the terms of 0 similarity (Fig. 1A).
2. **Reorganize**: The filtered terms in Murphy are used as the low-level term of the most similar in RFB. The reorganized functional database has four levels (Fig. 1B).
3. **Integrate**: Find the term that has the highest similarity with the fourth level in the reorganized functional database. If the term is in the second level, it is regarded as the low-level term of it. If the term is in third level, it is regards as a term at the same level (Fig. 1C).

After the above three steps, a functional database of three levels is obtained, which includes 839 functional terms, and 8 terms in the first-level, 128 terms in the second-level and 703 terms in the third-level (Table 1). External information provided to the designers are derived from this database.

2.1.2 Construct FCM Based on Functional Database

According to the similarity between function terms in database, a Fuzzy Cognitive Map (FCM) was constructed, and the functional terms with high relevancy to the target product were output through the analysis and reasoning mechanism of the FCM. The construction of FCM contains the following 5 steps.

1. Calculate the semantic similarity between every two function terms in the database, and get Initial Matrix (IM) according to the number of function terms and the value of similarity. IM is a matrix of [n × n], where the element O_{ij} represents the similarity between the word i and the word j, and the elements O_{i1}, O_{i2}, …, O_{im} of column i form the vector V_i.

Table 1. Part of Functional Database

First level	Second level	Third level
Branch	Separate	Divide, Extract, Remove, Spray
	Distribute	
	Clean	Wash, Splash, Grind
	Split	Partition, Tear, Fracture, Rip
	Break	Dab, Scrub, Fork, Shuffle, Punch, Gore, Shave, Shear, Burst, Rupture, Breach, Tap, Cascade, Shower, Snap, Bore
	Machine	Filter, Comb, Crater, Trim, Fan, Surface
	Miss	Pop
	Cube	Crack
	Screen	
	Polish	
	Bleach	
	Buff	Sweep
	Chafe	
	Network	
	Plow	
…		
…	…	…
8	128	703

2. The largest element in V_i is assigned a value of 1, the smallest element is assigned a value of 0, and the others are scaled to [0, 1] to obtain Fuzzy Matrix (FZM), the element of which is F_{ij}.
3. Relationship Strength Matrix (FSM) is derived from FZM, the element of which is S_{ij}. In the database, relationship between the adjacent levels is unidirectional, and the direction is from lower level to higher level. The relationship between terms in the same level is bidirectional. When a relationship exists, $S_{ij} = F_{ij}$; otherwise, $S_{ij} = 0$.
4. All the elements in the SRM are arranged in an ascending order, and elements smaller than 20% of the quantiles are defined as 0, and then Adjacency Matrix (AM) is obtained, the elements of which is W_{ij}.
5. W_{ij} represents the final relationship between the term i and the term j, the direction of which is from i to j. Finally, we got the FCM.

2.1.3 Obtain Functional Terms

The function terms that can represent the product functions are taken as input, and after the calculation and reasoning of the FCM, the functional terms that are closely related to target product are obtained.

According to the function of the target product, functional terms are obtained from the database, and the Input Vector (IPV) is obtained. IPV is an n-dimensional row vector, and $I_{1j} = 1$ when the word j is selected, otherwise $I_{1j} = 0$. The IPV is multiplied by AM to obtain the Middle Vector (MV), and the MV is converted to IPV^1 to use a binary compression function. IPV^1 is multiplied by AM as the next input vector until IPV^n is stable. According to IPV^n, the corresponding terms are found from the database, that is, the function terms that are closely related to target product.

2.2 Experiment Design

2.2.1 Subjects

In this experiment, 16 students with a background of engineering design from Beijing Institute of Technology were taken as designers, and they were divided into two groups randomly. The two groups have the same number of students, and named Group A and Group B respectively.

2.2.2 Provision of Functional Terms

The functional terms provided to Group A is closely related to the target product. The experiment selected *High-rise auxiliary escape tool* as the target product, and then obtained functional terms from the database in Sect. 2.1.1 that can represent the product function. They are "*drop, stop, steady, guard, retard, ground, balance*". According to Sect. 2.1.2, the output function terms are "*hold, position, grip, grasp, clasp, seat, place, rest, center, balance, assist, order, ground, posture, fit, pose, cinch, cradle, steady, drop, retard, guard* ".

2.2.3 Data Collection

- The EEG data of conceptual design process was collected by EMOTIV Epoc+, which is with 16 electrodes and both sides of the mastoid are reference electrodes. The EEG data recorded by EEG was 128 Hz.
- Product design results was collected by using the sketch method.

2.2.4 Experiment Process

The designers first read the experimental instruction to clarify the for the product design experiment. For Group A, 12 functional words were randomly selected from Sect. 2.2.1 as external information. Group B was not provided with external information. Designers need to think about 10 min or so, draw a solution and dictate realization for this problem immediately after thinking. The EEG of designers in the entire process of conceptual design was recorded. The experiment process is shown in Fig. 2.

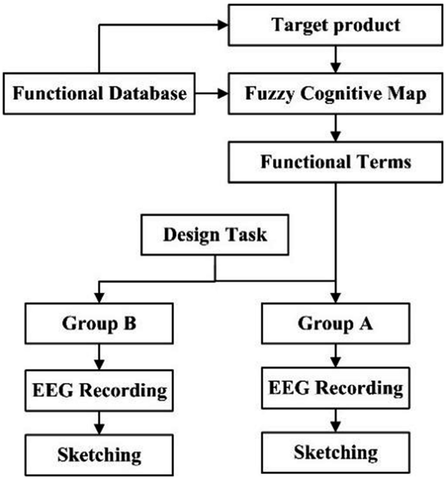

Fig. 2. Experiment process

3 Results and Data Analysis

EEG is a spontaneous, rhythmic discharge of the brain, and it is a non-linear, non-stationary electrophysiological signal [16]. Therefore, the analysis of EEG signals can use nonlinear parameters to characterize different neural activity states. In this work, sample entropy was selected as the complexity index to analyze designers' EEG, because of its good noise immunity [17].

We used a 1 s length window to calculate the sample entropy of the EEG, and select the parameters m = 2, r = 0.2SD. Based on this, the sample entropy was calculated, and then it was analyzed quantitatively and qualitatively.

Table 2. The mean EEG sample entropy of the designer at electrode F7, F8 and the T-test result

F7	A	Designer	1	2	3	4	5	6	7	8	P = 0.0356
		Sample entropy	0.5660	1.0899	0.6152	0.6057	1.1070	1.1730	0.8293	1.2387	
	B	Designer	9	10	11	12	13	14	15	16	
		Sample entropy	1.0985	1.3576	0.7619	1.2940	1.4065	1.3165	1.2836	0.9265	
F8	A	Designer	1	2	3	4	5	6	7	8	P = 0.0091
		Sample entropy	0.4769	1.0673	0.4229	0.5744	1.2944	1.6383	1.1836	0.6927	
	B	Designer	9	10	11	12	13	14	15	16	
		Sample entropy	2.0449	2.6683	0.5311	1.1635	1.9783	1.8364	1.5293	1.3826	

3.1 Quantitative Analysis

The sample entropy of EEG recorded by 14 electrodes in each group is shown in Table 2. The result was that the averaged sample entropy of group B (1.5741) was larger than that of group A (1.3488). We further made *T-test* on all 14 electrodes.

The *T-test* showed that the sample entropies of group B at F7 (P = 0.0356, left anterior temporal) and F8 (P = 0.0091, right anterior temporal) were higher than that of group A. There was no significant difference at other electrodes.

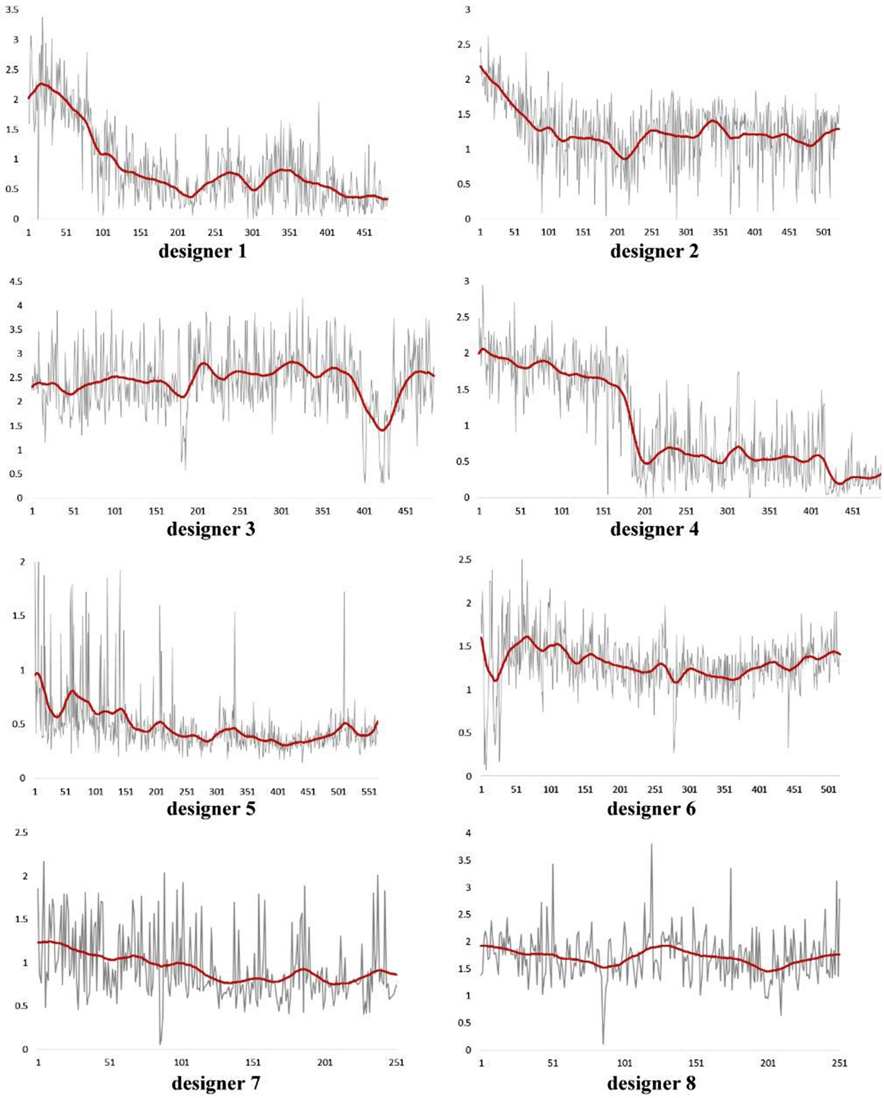

Fig. 3. Designers' trend of EEG sample entropy at electrode T7 in group A

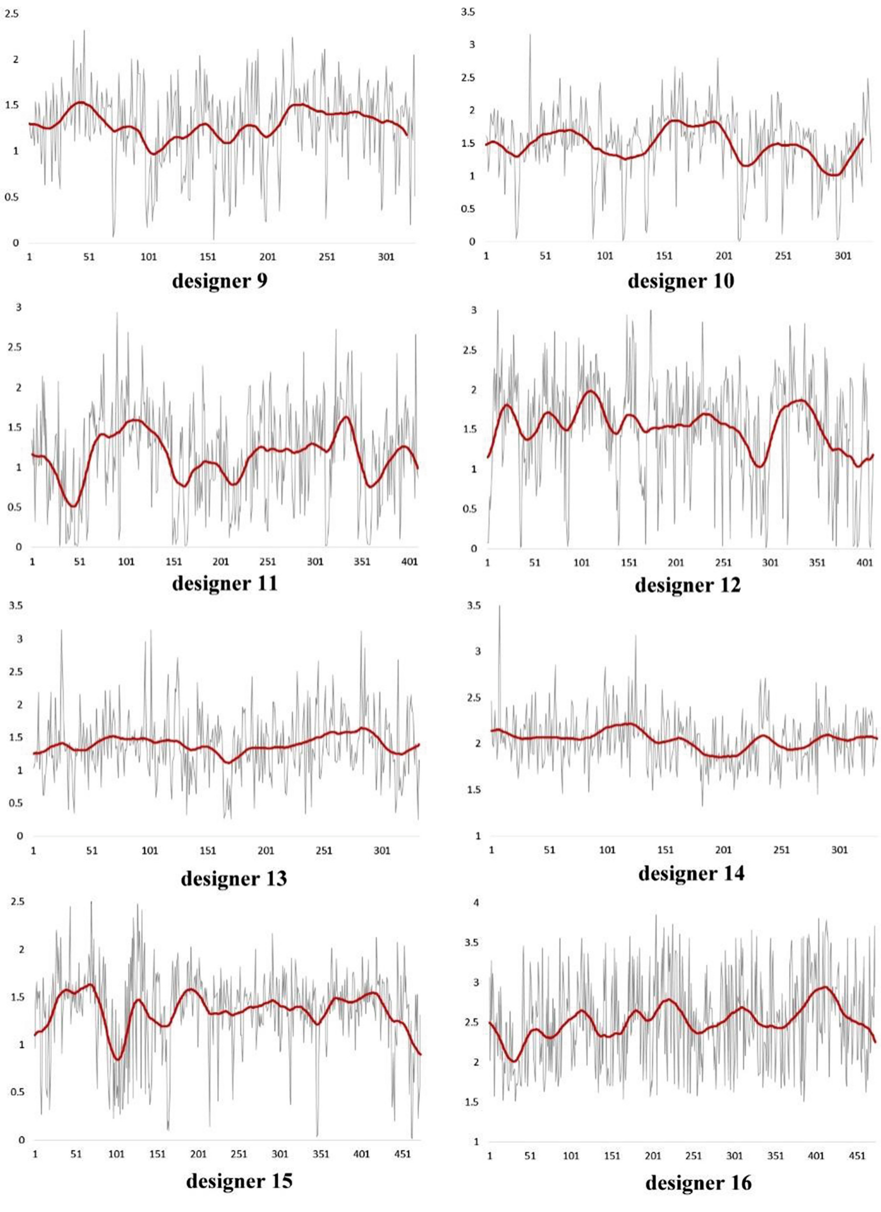

Fig. 4. Designers' trend of EEG sample entropy at electrode T7 in group B

3.2 Qualitative Analysis

We drew the trend of each window sample entropy. To reduce the impact of data fluctuations, we took a moving average method to process the data. The results were that the sample entropy of EEG in Group A was a shape of lower in the middle and higher on both sides at electrode T7 (left temporal lobe), T8 (right temporal lobe), P7 (left parietal lobe), P8 (right parietal lobe) and F8 (right anterior temporal) (Fig. 3). The sample entropy of Group B showed a stable or disorderly fluctuation (Fig. 4).

4 Discussion

Further, according to the position of the electrodes, we find the brain areas corresponding to the obtained brain electrical signal. Ratiocinate about how external stimuli affects design thinking is based on the function of brain partitioning and the characteristics of EEG. In 1909, Brodmann divided the cerebral cortex into 52 areas according to the type of cortical cells and the density of the fibers [18]. Currently, the study on the function of Brodmann Areas has been comprehensive [19].

The EEG is more complex when no functional terms were provided. Especially in the temporal polar, which is related to memory region. This finding may imply that without external stimuli, the memory of the designer awakens, which prompts the designer to associate other information and leads to complex brain activity. When provided with function terms closely related to the design problem, de-signers can obtain information from these function words for conceptual design, and the complexity of brain activity is relatively low.

When provided with external stimuli, the EEG complexity of the designer's inferior temporal gyrus, the temporal gyrus, the angular gyrus and the temporal pole region roughly follows a trend of first decreasing and then increasing. The inferior temporal gyrus is responsible for a high level of information processing, i.e. answering the question of what the information is. The temporal gyrus is the language processing area. Cornerback is part of the Wernicke District, located in the parietal lobe, with the function of semantic processing. The temporal polar regions are related to human memory.

When provided with external stimuli, the designers' brain are in a state of complex activity for information processing, language processing, and semantic processing. The designers first ponders over what the information provided is, and then manipulates the information. This process would awaken the designers' memory, which leads to complex brain activity. As the designer performs the conceptual design, this information has been transformed into working memory stored in the brain. In the process, the complexity of brain activity gradually decreases. Later in the conceptual design, the designer needs to perform semantic processing to output program-related information and generate a conceptual design. Once again, this complicates the designer's brain activity.

The complexity of the designer's brain activity remains stable or disorderly when no external stimuli is provided.

5 Conclusion and Future Work

The main purpose of this paper is to explore the impact of external stimuli on the designers' EEG features, and to ratiocinate the inner cognitive process of conceptual design based on EEG features. This paper selected functional terms as the external stimuli. We screened current functional terms and built a well-adapted inspiring database. Combining with FCM, we can deduce the functional terms that are closely related to target product. Obtained the designer's EEG and combined with the complexity of the analysis results and functional division of the brain, we can ratiocinate the process of design thinking.

Conclusions are as below:

1. Designers without any external stimuli have more complex brain activities than designers with external stimuli. This promotes the awakening of associations and memories, and the brain activity in this process is fluctuating.
2. When provided with external stimuli closely related to design problem, the designers awaken the memory during information processing and then it changes to working memory. Then designers output the conceptual design after the semantic processing. In the process, the complexity of brain activity first decreases and then increases.

Future work is to partition the conceptual design process according to the characteristics of EEG and select relevant indicators to summarize the EEG features and thinking characteristics of each area. Moreover provide different external stimuli according to the different thinking features that the designer presents in the conceptual design areas to assist the designers.

Acknowledgments. The authors would like to thank the anonymous reviewers for their valuable comments and thank the strong support provided by National Natural Science Foundation of China (NSFC 51505032) and Beijing Natural Science Foundation (BJNSF 3172028).

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