IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 13 May 2023, accepted 29 July 2023, date of publication 1 August 2023, date of current version 9 August 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3300800

RESEARCH ARTICLE

Research on Innovative Method of Human–Computer Collaborative Aesthetic Education Based on Hybrid of Neuroaesthetics and Shape Grammar

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This work was supported by the Research and Development Program of Beijing Municipal Education Commission under Grant SM202310005009.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Science and Technology Ethics Committee of Beijing University of Technology.

ABSTRACT This paper proposed an innovative method for aesthetic education by integrating shape grammar and neuroaesthetics. Aesthetic education can be divided into bottom-up aesthetic cultivation and top-down knowledge education, which correspond to the characteristics of shape grammar and neuroaesthetics, respectively. In this study, we redefined the state space of traditional shape grammar by replacing the computer-dominated label set with the affective-dominated emotion set of neuroaesthetics. This resulted in a neuroaesthetic shape grammar that is led by the designer and complementary to human intuition and algorithmic logic. We validated this method through practical design cases in the field of aesthetic education.

INDEX TERMS Aesthetic education, design thinking, human–machine collaboration, neuroaesthetics, shape grammar.

I. INTRODUCTION

''Aesthetic education'' cultivates students' aesthetic sensibility and ability in a bottom-up manner unconsciously, while ''education'' imparts specific knowledge of a discipline in a top-down manner [1], [2]. Therefore, the ''education'' in ''aesthetic education'' is not only the education of aesthetic theories and knowledge, but more accurately, it is cultivating and nurturing the aesthetic perceptions and experiences [3]. ''Education'' is a unidirectional transfer of knowledge information, where teachers impart knowledge to students in a top-down manner, and students often passively receive knowledge as objects. In contrast, ''cultivation'' emphasizes creating a growth environment where students can fully exercise their autonomy, actively acquire abilities and acquire knowledge through iterative upgrades and experiential accumulation in a bottom-up manner [4]. Both bottom-up ''aesthetic cultivation'' and top-down ''education'' are indispensable for cultivating students' aesthetic abilities [5]. Aesthetic education can naturally and unconsciously cultivate students' aesthetic sensibility, while education can efficiently and accurately provide knowledge about aesthetics [6]. This paper refers to this process of equal emphasis on bottom-up and top-down processes as ''aesthetic cultivation and education'', in brief aesthetic education in the following text.

The associate editor coordinating the review of this manuscript and approving it for publication was Daniela Cristina Momete.

This paper explores innovative methods for aesthetic education by combining shape grammar and neuroaesthetics. shape grammar is based on computational logic, which has the computer-based characteristics of objectivity and formulization, while neuroaesthetics is based on human aesthetic intuition and perception of the outside world by the ''Visual Brain [7]'', which has the human-based characteristics of subjectivity and emotionalization. By combining the

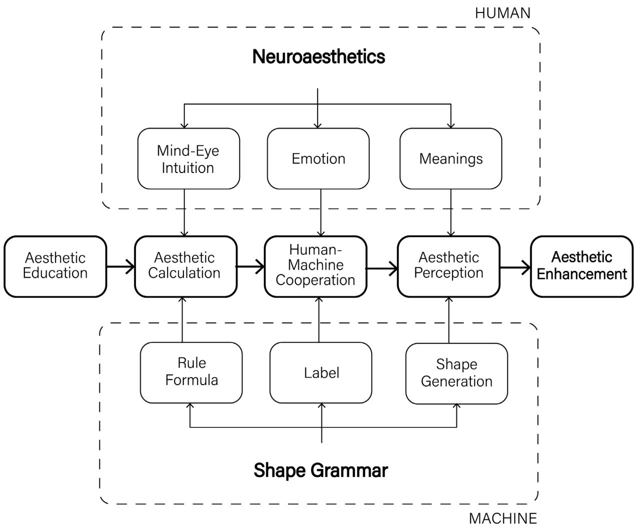

FIGURE 1. Research pathway of exploring innovative methods for art education through the integration of shape grammar and neuroaesthetics.

two, the advantages and characteristics of each can be fully utilized. Figure 1 illustrates the research path and technical pipeline of this study, which focuses on research on aesthetic education and integrates the technical elements of shape grammar and neuroaesthetics.

The technical elements of shape grammar include shape rule formulas [8], labels under computer operation mechanisms [9], [10], [11], and the self-organizing process of shape generation [12]. The common feature of these elements is the bottom-up logic based on computer algorithms, which has objectivity. Since shape grammar is an automated iterative program based on computer algorithms, it also has the characteristics of simplicity and ease of operation. If the computer algorithm and program in the iterative calculation process of shape grammar are replaced by the direct participation of designers, using the generative design logic of shape grammar with the addition of intuition and subjective aesthetic decision-making, the efficiency of the shape design process can be greatly improved. At the same time, the objectivity of shape grammar as a shape generation mechanism can assist the designer's aesthetic thinking during the design process, thus stimulating the designer's neural aesthetic triad system in the visual brain and helping the designer enhance their sense of beauty [13].

The technical elements of neuroaesthetics interact with the technical elements of shape grammar in a top-down logic: designers rely on aesthetic intuition, use hand-eye coordination to replace computer algorithms, and directly use shape rules to complete aesthetic calculations; designers need to rely on their own emotional feelings to guide the process of shape iteration taking over the role of data labels originally used in computer algorithms; designers assign meaning to shapes in real time efficiently according to the iterative results of shape grammar calculations, enabling shapes to gradually become artistic design works while gradually enhancing their own artistic perception in the process, ultimately achieving the goal of improving designers' aesthetic sense through aesthetic education.

II. SHAPE GRAMMAR AESTHETIC COMPUTATION AND CALCULATION

A. SHAPE GRAMMAR

Shape grammar [14], [15] is a type of grammar system that abstracts a series of intuitive and complex design rules into a computer-understandable system, allowing designers to use computers to automate the rapid generation and iteration of design solutions, thereby improving the efficiency of the design workflow. Based on mathematical logic, shape grammar transforms emotional aesthetic design problems into rational quantitative research problems [16], [17]. Typically, shape grammar uses a set of grammar rules and an initial shape to iteratively apply the grammar rules to the initial shape and the current shape, resulting in new shapes and design outcomes [18].

As shown in Figure 2, a shape grammar is generated to create an external rectangle, where (a) represents the initial shape, and (b) represents a set of custom shape rules. The dots on the quadrilateral in (a) are labels for the initial shape, which the computer uses to recognize and perform iterative operations. In the shape rules, rule (1) resizes the initial quadrilateral proportionally and rotates it 45 degrees to generate an external rectangle, while rule (2) removes the label dots on the initial quadrilateral. These two shape rules constitute a simple shape grammar, and by executing this shape grammar on a computer, the shape design and its iterative design process shown in Figure 3 can be obtained [19], [20].

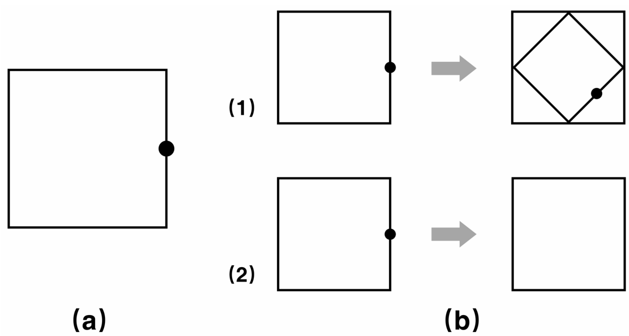

FIGURE 2. Shape grammar and shape rules [20].

B. STATE SPACE

The collection of all constituent elements, including the grammar rules, initial shape, and current shape, involved in the construction of the above-mentioned shape grammar is referred to as the state space of this shape grammar. The state space is a formal definition, where researchers present problems, constraints, variables, and conditions in a formal (mathematical) way to the computer before performing computational operations [21]. The computer can understand

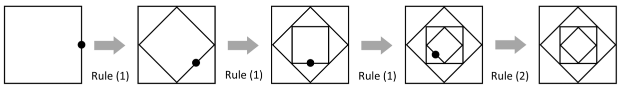

FIGURE 3. Iterative design process using shape grammar [20].

the problem to be solved based on the parameters of the state space, in order to implement algorithms [22]. The state space of shape grammar consists of four subsets [23], [24], which can be summarized as follows in this paper:

$$SG = (I, L, R, S) \tag{1}$$

In the equation(1), SG represents shape grammar; S is the set of current shapes; L is the set of shapes with labels, which indicates the objects to which the grammar rules are applied; R is the set of shape rules, such as rules (1) and (2) mentioned in Figure 2; and I is the set of initial shapes, which also have labels and is a subset of L. Based on the state space, the algorithm engineer can program based on the shape grammar and make the computer automatically execute all commands to achieve intelligent automation of computational design [25].

C. COMPUTING VS CALCULATING

The author of shape grammar, George Stiny, believes that the commonly known computational design, which relies on computer-based computing technology, although it is the technical basis of shape grammar, computing does not equal design (Computing $\neq$ Design). This is because computing is binary and belongs to a low-dimensional and simple data processing form, while high-dimensional and complex data processing form is human-based calculating, which incorporates human intuition, emotion, experience, and subjective aesthetic decision-making. For example, "Firmitas, Venustas, Utilitas" are three standards proposed in "Ten Books on Architecture [26]" for architectural design, and binary computing can only solve the problem of "Firmitas," while human subjective intuition and calculation can handle more complex problems of "Venustas" and "Utilitas." Therefore, Stiny believes that design cannot be separated from the designer's design thinking, subjective aesthetic intuition, and decision-making, and he proposed that design equals human subjective calculation (Design = Calculating) [27].

Computer-based computation transforms everything, objects, and problems into data, and uses data as the basic material. Based on the ontological logic of objective things at the data level, it explores the essential rules behind the data and research objects. The shape grammar based on the mechanism of computer computation is objective, bottom-up, simple, and programmable. In contrast, human-based calculation transforms all external factors into subjective cognition, based on the epistemological logic of top-down cognition. It relies on the subjective secondary processing of objective things, including intuition, experience, emotions, and other factors, and the basis of this processing mechanism is the "visual brain [7]" of humans and a series of neural signal transmissions. The shape grammar based on human calculation is subjective and complex, and difficult to program into computer code. For example, the checker shadow illusion experiment [28] can well reveal the essential differences between computer computation and human calculation. In Figure 4, the left side is what the human visual brain sees after calculation, and the right side is what the computer sees after computation. In the two squares A and B of the chessboard, the colors we see from the figure are different, but in fact, the colors in the two squares are the same. This is the result of the human visual system's "illusion." In fact, what the retina sees is consistent with the picture, but the image information is transmitted to the visual cortex and undergoes a series of processing by the subsequent "visual brain," producing the visual image that conforms to our cognitive logic and can be understood by our cognitive system. In other words, the left side is the result of our epistemology, and the right side is the real reflection of ontology of things. If our "visual perception system" can recognize the same color directly from points A and B in the figure without any auxiliary means like a computer, then our "visual perception system" may have something trouble [29]. This experiment reveals a fact that the world we see is not real or objective, but a world changed by our "visual brain" through "top-down" processing, and it proves that our brain's vision is the result of human calculation.

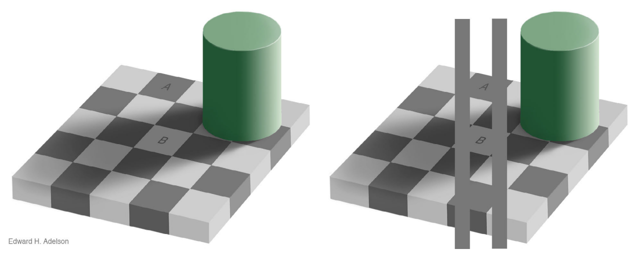

FIGURE 4. Checker shadow illusion [28].

Therefore, creative activities cannot be separated from human subjective aesthetics and intuitive calculation. Human calculation can effectively and rapidly handle complex problems in a top-down manner, so it is necessary to deeply understand the operation mechanism of the visual brain. Neuroaesthetics provides important theoretical and methodological support for this.

III. THE NEUROAESTHETICS TRAID

Neuroaesthetics is an emerging discipline that studies the structure and mechanisms of aesthetic experience on the basis of neuroscience, exploring the biological basis of aesthetics, and using empirical neuroscientific principles to further explain aesthetic phenomena [30]. Aesthetic experience is often accompanied by aesthetic judgment and emotional changes. This is because aesthetic experience includes the emotions, values, and behaviors generated by aesthetic objects, as well as the processes of interpretation and generation. That is, how aesthetic experience is generated instantaneously in the brain and how the brain mechanism helps us to understand these experiences. Neuroaesthetics combines empirical aesthetics with cognitive and affective neuroscience to systematically explain aesthetic activities.

Neuroaesthetics can take descriptive or experimental forms. Descriptive neuroaesthetics relies on observations that link brain facts to aesthetic experience, typically qualitative in nature [31]. Experimental neuroaesthetics, like other experimental sciences, produces quantitative data that is statistically analyzed to obtain experimental results, typically quantitative in nature [32].

Chatterjee and Vartanian proposed the Aesthetic Triad theory [33], [34] in 2014, which suggests that aesthetic experience arises from interactions among three systems: the sensory-motor systems, the emotion-valuation systems, and the knowledge-meaning systems (as shown in Figure 5). They also propose that the best aesthetic experience occurs when all three systems are simultaneously activated, and this can enhance aesthetic ability [35]. This theory is an important theoretical basis for innovation research in aesthetic education.

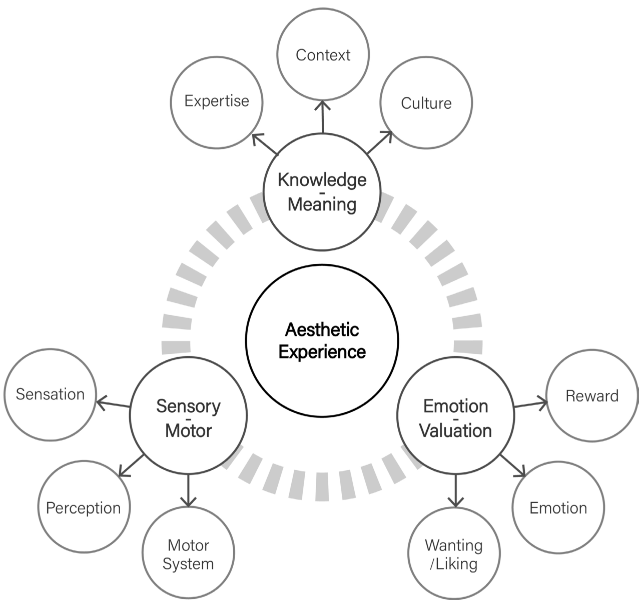

FIGURE 5. The aesthetic triad system in neuroaesthetics [33].

Mapping various aspects of information processing to specific neural network structures is a cornerstone of neuroaesthetics [36]. For example, early and mid-level processing of visual aesthetics, such as brightness and color processing and classification, occurs in relevant parts of the occipital lobes, with higher-level visual occurring in the fusiform gyrus (such as the face area in the fusiform gyrus) and medial temporal lobes (such as the location area in the parahippocampal gyrus), as well as implicit behaviors in the motor system (such as the mirror system). These findings confirm the role of the aesthetic triad system in the automatic processing of the basic features of aesthetic objects, and their involvement in aesthetic recognition and engagement through specific mechanisms.

IV. RECONSTRUCTION OF SHAPE GRAMMAR BASED ON NEUROAESTHETICS

The neuroaesthetic-based shape grammar proposed in this study is a new aesthetic calculating and computing method that combines human intuitive aesthetic calculation with computer-based algorithmic computation. In this method, designers take over the role of computers in traditional shape grammar and, as design subject, directly operate the grammar for aesthetic calculation and design iteration. In other words, designers transplant the workflow of traditional shape grammar for algorithmic computation from computers to their own design workflows, which has two advantages. First, since shape grammar is based on the computation mechanism of computers, it has the characteristics of formulization, simplicity, and ease of operation. When designers apply this attribute to their workflow, it can greatly reduce the difficulty of design, especially for those who have weak foundations in aesthetics. This formulized and mathematical aesthetic computation logic can help them quickly produce design results. Second, designers, as the operators of the shape grammar, integrate the triadic mechanism of neuroaesthetics into the iteration and design workflow of shape grammar. On the one hand, this integration can quickly produce the best aesthetic design judged by the designer's aesthetic intuition. On the other hand, this training can effectively improve the designer's aesthetic ability and design innovation ability, thanks to the activation of the three systems of neuroaesthetics.

A. DEFINING SHAPE RULES

This study defines three sets of shape rules, namely "part", "boundary", and "transformation" (see formulas 2, 3, and 4), as following:

•"Part" refers to creating new shapes by extracting and isolating "parts" of the original shape x.

$$x \rightarrow prt\,(x) \tag{2}$$

•"Transformation" refers to creating new shapes by transforming (e.g. translating, rotating, reflecting) the initial shape x.

$$x \rightarrow x + t\,(x) \tag{3}$$

•"Boundary" refers to extracting the contour or boundary of the initial shape x to obtain a new shape.

$$x \rightarrow b\,(x) \tag{4}$$

These three sets of shape rules simulate human designer's intuitive thinking and are easy to be practically operated by designers during the iterative calculation process of shape grammar. Through various arrangements and combinations of these rules, they can generate diverse and complex computational design shapes (as shown in Figure 6).

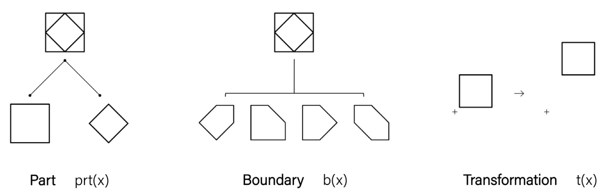

FIGURE 6. The three sets of shape rules in the shape grammar of this study.

B. DEFINING THE STATE SPACE

The formal definition of the shape grammar constructed by the above three sets of shape rules, namely the state space, is shown in Figure 7. Similar to the state space of traditional shape grammar, it consists of four subsets:

$$SG' = (I, E, R, S) \tag{5}$$

The partial elements in formula (5) are similar to those in formula (1), where SG' represents the new shape grammar constructed in this study; S is the current set of shapes; R is the set of shape rules; and I is the initial set of shapes. What differs from the formula (1) lies in the set E, which represents the set of emotional elements, replacing the label set L in formula (1). This innovation of using human emotions and intuitions instead of computer labels and codes, as well as using human top-down "calculative" wisdom instead of computer bottom-up "computational" intelligence, is the highlight of the shape grammar constructed in this study [37].

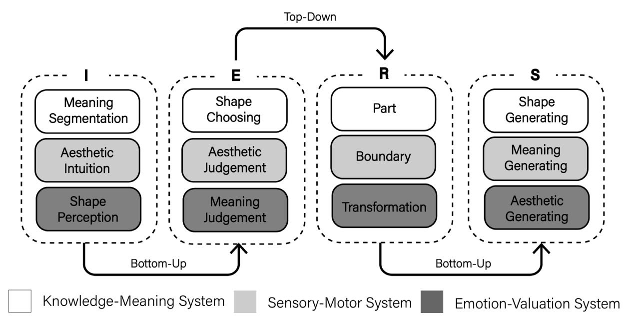

FIGURE 7. The state space of the shape grammar in this study.

The aim of this study is to construct a shape grammar that can simultaneously activate the three systems of neuroaesthetics triad. In Figure 7, the white, light gray, and dark gray colors represent the activated states of the "Knowledge-meaning," "Sensory-motor," and "Emotion-valuation" systems of neuroaesthetics, respectively. It can be observed that in the four sets of the state space of the shape grammar constructed in this study, all three systems of neuroaesthetics triad are activated simultaneously.

In the initial shape set I, i.e., the process of extracting initial shapes in the first stage, the designer needs to select initial shapes from given sources of inspiration such as paintings, imagery etc. According to the Gestalt psychology theory of visual perception, when people receive visual information, they first perceive the shape through the retina and visual cortex in a bottom-up manner [38], [39]. Then, the "visual brain [4]" will segment the visual clues into meaningful parts through "segmentation [40]", and perceptually group them into different structures with different meanings through "perceptual grouping [41], [42]" or "figure-ground segregation [43]", this whole process is called "semantic segmentation [44]". "Shape perception" and "semantic segmentation" correspond to the activation state of the "sensory-motor" and "knowledge-meaning" systems in the brain, respectively, while the "emotion-valuation" system has been activated at the early stage of this process. While obtaining visual clues from the imagery source, the designer's "emotion-value" system and aesthetic intuition start to play the role. On the one hand, the designer will make an initial judgment based on his/her intuition. On the other hand, the visual clues provide the designer with references and inspiration, which further stimulate the designer's aesthetic intuition.

In the emotion set E, the elements of human designers fully exerting their subjectivity in the workflow converge here. Based on intuition and aesthetic preferences, designers make "shape selection" in the given inspiration source images, and this action involves the activation of the "sensory-motor" system as shapes change due to movement. At the same time, behind this change, designers make two judgments: one is "aesthetic judgment", that is, whether the selected shape conforms to their inner aesthetic preference, driven by the "emotion-valuation" system. The other is "meaning judgment", that is, choosing the shape is based on certain meaningful considerations, which involves the "knowledge-meaning" system.

The set R represents the state space of shape rules, and the three groups of shape rules in this study were established based on the neuroaesthetics triad system. The rules in the "part: $prt\,(x)$"and "boundary: $b\,(x)$" groups are driven by both the "knowledge-meaning" and "emotion-evaluation" systems simultaneously or a single system alone. For example, the group of rules "part: $prt\,(x)$" may be driven by 60% of the "knowledge-meaning" system and 40% of the "emotion-evaluation" system, depending on the designer's ratio of "meaning judgment" and "aesthetic judgment" in the emotional set E when using the shape rules. In this case, 60% of the designer's decision is based on thinking about meaning, and the remaining 40% is based on aesthetic considerations. Similarly, this feature also applies to the "boundary: $b\,(x)$" rules. The "transformation: $t\,(x)$" rule is mainly driven by the "sensation-movement" system. When using the "transformation" rule, designers can not only create more creative new shapes through a series of shape transformations, but also stimulate the "sensation-movement" system through the deformation and movement of shapes, inspiring the aesthetic creative potential of the visual brain, thereby enhancing the designer's aesthetic sense.

The set S represents the current set of shapes, which is the latest shape generated after the application of a set of shape rules. ''Shape generating'' occurs firstly at this stage, and the most relevant neural mechanism is ''sensory-motor'', as designers gain inspiration from each newly generated shape obtained through the iteration of the shape grammar, to think about the new stage of shape rules and aesthetic calculations. With shape generation, ''meaning generating'' or ''aesthetic generating'' occurs, corresponding to the ''knowledge-meaning'' and ''emotion-evaluation'' systems in the neural aesthetics system. Therefore, whether this stage reflects ''meaning'' or ''aesthetics'' in the shape depends on the designer's subjective cognition of the latest shape.

C. WORKFLOW DESIGN

The integration of neural aesthetics and shape grammar combines subjectivity and objectivity, sensibility and rationality, emotion and logic (formulas), and top-down and bottom-up processes. The specific manifestation of the state space in the workflow is shown in Figure 8, where the bottom right corner represents the shape calculation unit under the action of a set of shape rules, and the top left corner represents the shape grammar calculation process of multiple iterations of multiple shape calculation units. The process is composed of multiple shape calculation units superimposed on each other.

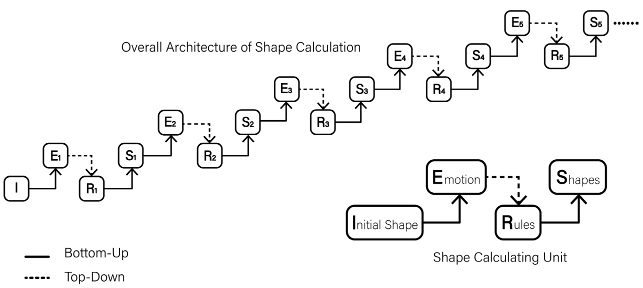

FIGURE 8. **The unit and overall architecture of shape calculation.**

In the shape computation unit in the lower right corner of Figure 8, the connection between the state space sets can be classified into two categories: bottom-up and top-down, represented by solid and dashed lines respectively in the figure. In this study, the bottom-up approach emphasizes the objectivity of the computation process, while the top-down approach emphasizes the subjectivity of the calculation process. In the shape calculating unit, the aesthetic calculation is divided into three stages: (1) the process from the initial shape set I to the emotion set E is a bottom-up generation process. During this process, designers are inspired by objects including visual art sources and initial shapes, which stimulate their own aesthetic emotions as the subject, and in turn, stimulate the creativity of their aesthetic abilities. It is this process, in which the subject is inspired by the object, that is the bottom-up generative design process. (2) Next, the design subject exerts the design inspiration and aesthetic decisions obtained from the previous stage through the emotion set E to construct a subjective rule system that determines how objective shape rule formulas in the shape rule set R are used. This process is a top-down approach where the subject acts on the object to perform aesthetic calculation. (3) The shape rule set R receives the aesthetic computation instruction from the previous stage, and applies the shape rules to the initial shape to obtain the current shape set S. This process is similar to parametric design and computer operation, where the initial shape and shape rules construct a self-organizing system. The shape rules act on the system according to established instructions, and new shapes are generated by the system in a bottom-up manner.

The above shape computation units are extended and iterated in the architecture shown in the upper left part of Figure 8 to form a complete shape grammar. The current shape generated by the previous shape calculating unit is added as the initial shape to the new shape calculation iteration process of the next group of shape calculating units. The connection lines in the figure are drew as solid and dashed to distinguish between the bottom-up and top-down processes. The aesthetic calculation process of the entire shape grammar is a collaborative design process that integrates and iterates between the subject and object, involving both top-down and bottom-up processes.

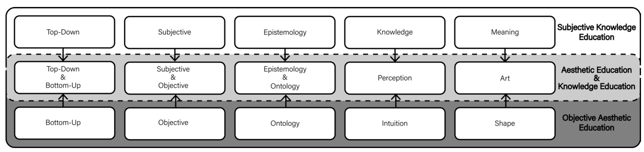

FIGURE 9. **Overlapping mechanism of aesthetic education and knowledge education.**

FIGURE 10. **The shape grammar design practice work of this research.**

V. THE APPLICATION RESEARCH ON AESTHETIC EDUCATION

A. AESTHETIC EDUCATION

The aim of this study is to explore innovative methods and paths for aesthetic education based on the combination of

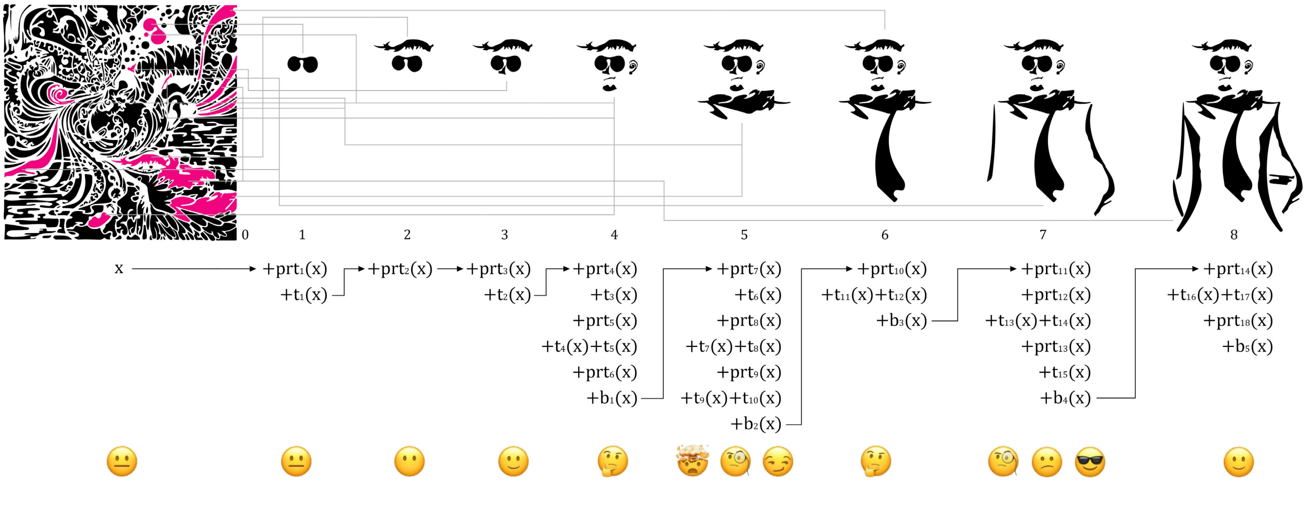

FIGURE 11. The workflow of shape grammar case study in this research.

neuroaesthetics and shape grammar design. The concept of "aesthetic education" is a combination of bottom-up aesthetics cultivation and top-down knowledge education [45], as shown in Figure 9. Aesthetic education is objective and based on the impact and inspiration of object shapes on the subjective designer. It is ontological and follows a bottom-up logic of objective things [46], [47]. In this system of subject and object, objects silently influence the subject to form aesthetic feelings and intuitions in a bottom-up manner. In contrast, education is subjective and based on the subject's cognition and understanding of objects. It follows an epistemological logic of subjective cognition. In this system, the subject learns and grasps the knowledge and significance of aesthetics in a top-down manner [48].

The neural aesthetic shape grammar developed in this study exhibits objectivity and formulaic operations in the bottom-up art aspect, while subjectivity and aesthetic computation in the top-down education aspect. This method leverages the objectivity, simplicity, ease of operation, and programmability of shape grammar design while activating the neural aesthetic triad system and unleashing the subject's subjective aesthetic cognition. The visual brain's ability to solve complex aesthetic computing problems is also utilized. Under the dual effects of neural aesthetics and shape grammar, a complete aesthetic education mechanism is formed as shown in the overlapping part of Figure 9. This mechanism is a superposition of multiple levels, including bottom-up and top-down, objectivity and subjectivity, ontology and epistemology [49]. In this overlapping state, the aesthetic intuition formed through aesthetic education and the aesthetic knowledge acquired through education are combined to form aesthetic perception. In the process of gradually forming aesthetic perception and cognition, the subject designer continually gains insights into the nature of art and understands the essence of art. At the level of aesthetic cultivation, the subject's aesthetic intuition is based on the object shapes generated during iterative operations of the aesthetic computing process [50]. On the education level, the knowledge acquired by the subject originates from the new meanings that emerge when the shape changes occur every time. At this level, the objectivity of shape and the subjectivity of meaning superimpose, giving birth to art, which is the process of aesthetic perception for understanding art.

B. THE APPLICATION CASE

To verify the neural aesthetic shape grammar proposed in this study, the author taught this method to students in the course and guided them to apply it in their design practices. Figure 10 shows a typical case of an art creation completed by a student using the neuroaesthetic shape grammar. The left image is the source of inspiration or the initial shape, and the right image is the completed art piece. From the left image to the right image, the initial shape not only underwent significant changes but also its meaning and aesthetic were sublimated. The two pictures before and after the design even seem to have no relationship, which is the characteristic of this research method.

The author required the students to record the shape rules used and the changes in shape and emotions during each iteration process in the design process, using the format shown in Figure 11. The record chart is divided into three rows: the top row shows the shape iteration process, the middle row shows the use and deduction process of shape rules, and the bottom row shows the designer's emotional record during each iteration process. In this way, we can explore the aesthetic calculating process, i.e., the intermediate steps of changes in these two images. The records show that the student underwent eight shape iteration processes during the design of this work, and the shape rule calculation process corresponding to each shape change was recorded. Among the steps where the shape rules were used more frequently, it can be seen that the author's emotions also underwent significant fluctuations during the thinking process, such as the 5th and 7th steps.

The author interviewed the student, and according to the student's recollection of the recorded shape grammar calculation process, the student was able to recall every thought and idea from each step. According to the student's recollection, she was impressed by the "glasses" shape when she first saw the inspiration image, so she extracted it as the initial shape. Then she found shapes such as "hair" and "nose" from the visual elements of the inspiration image, and her emotional state at this time was a gradually satisfying state. In steps 4-5, after finding the "mouth" and "beard" shapes, the student faced a bottleneck and spent a great deal of effort finding the appropriate shape to depict a "scarf" and her emotional state changed in a short period of time. In the 5th step, there was initially anxiety and doubt during brainstorming, but with the satisfactory shape designed, the student's emotional state changed from negative to positive and became happy. This kind of emotional fluctuation reappeared in steps 6-7, where the student spent a lot of effort perfecting the "scarf" shape, then continuously experimented and searched for a suitable contour shape to depict the "dress". In the 7th step, the student experienced negative emotions such as doubt and disappointment but became positive after drawing a shape that satisfied herself. Finally, in the 8th step, the student added details and improved the design on the basis of the shapes created in the previous steps, ultimately achieving a satisfying design that made herself smile.

VI. CONCLUSION

This study combines the triad theory of neuroaesthetics and the computational design methodology of shape grammar to propose an innovative approach to design based on neuroaesthetics and shape grammar, as well as a novel path for aesthetic education. In formalizing the definition of the state space, this study introduces the emotion set E to replace the label set L in traditional shape grammar. Replacing computer algorithm simulations with human design participation, and leveraging human subjective aesthetic decision-making ability in the design process, inspiration and efficiency are based on human aesthetic intuition. The process is formalized by simple and logical shape grammar, and the design innovation is carried out through a combination of bottom-up and top-down shape grammar. On the one hand, this new method not only helps designers quickly and efficiently generate design solutions, and on the other hand, it provides greater benefits for designers' aesthetic formation and perceptual enhancement based on aesthetic education.

The author concluded the theoretical and practical research results of this article, and summarized the relationship between aesthetic education and neural aesthetic shape grammar, further demonstrating the academic contribution of the theoretical and innovative methods constructed in this research to aesthetic education. As shown in Figure 12, the three circles represent the three systems in the neuroaesthetics triad theory corresponding to the three activities of aesthetic education. The middle top circle represents the "emotion-valuation" system, corresponding to the "aesthetic" activity; the left bottom circle represents the "sensory-motor" system, corresponding to the "intuitive" activity; and the right bottom circle represents the "knowledge-meaning" system, corresponding to "knowledge"-related activities. According to the neuroaesthetics triad theory, when the three systems are activated at the same time, the brain reaches the optimal state of aesthetic perception and cognition. The author represents the activation state of the neural aesthetic system in Figure 12 by superimposing diagrams. When the "emotion-valuation" and "sensory-motor" systems are activated, the corresponding "aesthetics" and "intuition" activities occur simultaneously. The combination of these two activities enables the subject to engage in self-aesthetic education from the bottom-up and thus form "aesthetic sense." At the same time, when the "emotion-valuation" and "knowledge-meaning" circles are lined, the "aesthetics" and "knowledge" jointly affect the subject's aesthetic experience and consciousness, forming an educational tool "art education" that enable the subject to acquire aesthetic knowledge from the top-down. When the "sensory-motor" and "knowledge-meaning" circles are connected, the "knowledge" from the top-down and the "intuition" from the bottom-up interact to form the subject's perception of aesthetic cognition that combines the top-down and bottom-up processes. In summary, the core area of "aesthetic education" in the figure is not only the superposition

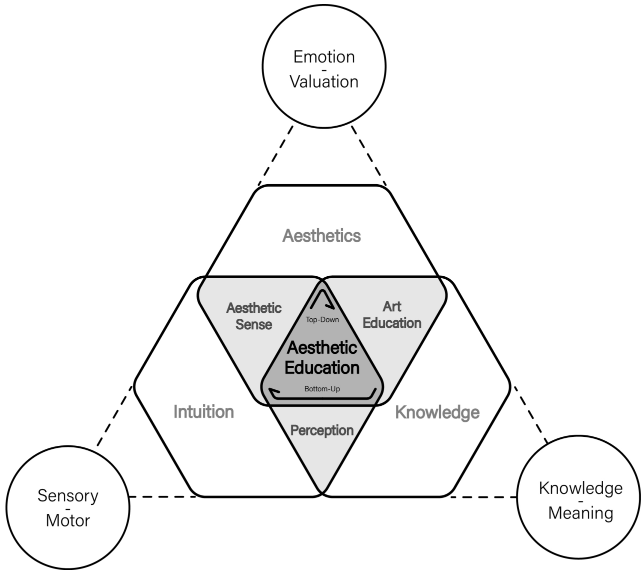

FIGURE 12. The relationship between aesthetic education and neuroaesthetic shape grammar.

and simultaneous activation of the three systems in neural aesthetics but also the superposition and simultaneous activation of the three conscious activities of intuition, aesthetics, and knowledge. These three conscious activities are activated together in the specific way of bottom-up and top-down aesthetic "perception" to perceive the bottom-up "beauty" and understand the top-down "art".

ACKNOWLEDGMENT

The authors would like to thank the undergraduate students from the Industrial Design Department, School of Art and Design, Beijing University of Technology, for their valuable contributions as participants in this research.

REFERENCES

[1] G. C. Spivak, *An Aesthetic Education in the Era of Globalization*. Cambridge, MA, USA: Harvard Univ. Press, 2013.
[2] M. Fullan, "Coordinating top-down and bottom-up strategies for educational reform," in *Systemic Reform: Perspectives on Personalizing Education*. Ann Arbor, MI, USA: Univ. of Michigan Library, 1994, pp. 7–24.
[3] F. Schiller, *On the Aesthetic Education of Man*. London, U.K.: Penguin, 2016.
[4] G. Skedsmo and S. G. Huber, "Top-down and bottom-up approaches to improve educational quality: Their intended and unintended consequences," *Educ. Assessment, Eval. Accountability*, vol. 31, no. 1, pp. 1–4, Feb. 2019.
[5] M. Pelowski, P. S. Markey, M. Forster, G. Gerger, and H. Leder, "Move me, astonish me··· delight my eyes and brain: The Vienna integrated model of top-down and bottom-up processes in art perception (VIMAP) and corresponding affective, evaluative, and neurophysiological correlates," *Phys. Life Rev.*, vol. 21, pp. 80–125, Jul. 2017.
[6] R. M. Hogarth, *Educating Intuition*. Chicago, IL, USA: University of Chicago Press, 2001.
[7] I. Kovács and B. Julesz, "Perceptual sensitivity maps within globally defined visual shapes," *Nature*, vol. 370, no. 6491, pp. 6–644, 1994.
[8] M. Tapia, "A visual implementation of a shape grammar system," *Environ. Planning B, Planning Design*, vol. 26, no. 1, pp. 59–73, 1999.
[9] J. Gips, *Computer Implementation of Shape Grammars; Proceedings of the NSF/MIT Workshop on Shape Computation*. Cambridge, MA, USA: Massachusetts Institute of Technology, 1999.
[10] M. Lipp, P. Wonka, and M. Wimmer, "Interactive visual editing of grammars for procedural architecture," *ACM Trans. Graph.*, vol. 27, no. 3, pp. 1–10, Aug. 2008.
[11] T. W. Knight, "Shape grammars: Six types," *Environ. Planning B, Planning Design*, vol. 26, no. 1, pp. 15–31, 1999.
[12] J. R. Speller and H. Thomas, "The use of shape grammar-cellular automata for modeling molecular dynamics," *J. Comput. Theor. Nanoscience*, vol. 6, no. 10, pp. 2179–2193, 2009.
[13] P. Sarasso, M. Neppi-Modona, and K. Sacco, "Stopping for knowledge': The sense of beauty in the perception-action cycle," *Neurosci. Biobehavioral Rev.*, vol. 118, pp. 723–738, Nov. 2020.
[14] G. Stiny and J. Gips, "Shape grammars and the generative specification of painting and sculpture," in *Proc. IFIP Congr.*, 1971, p. 1–9.
[15] G. Stiny, "Introduction to shape and shape grammars," *Environ. Planning B, Planning Design*, vol. 7, no. 3, pp. 51–343, 1980.
[16] T. Knight and G. Stiny, "Making grammars: From computing with shapes to computing with things," *Design Stud.*, vol. 41, pp. 8–28, Nov. 2015.
[17] I. Dieronitou, "The ontological and epistemological foundations of qualitative and quantitative approaches to research," *Int. J. Econ., Commerce Manag.*, vol. 2, no. 10, pp. 1–17, 2014.
[18] S.-W. Hsiao and C.-H. Chen, "A semantic and shape grammar based approach for product design," *Design Stud.*, vol. 18, no. 3, pp. 96–275, 1997.
[19] G. Stiny, "Ice-ray: A note on the generation of Chinese lattice designs," *Environ. Planning B, Planning Design*, vol. 4, no. 1, pp. 89–98, Jun. 1977.
[20] G. Stiny and J. Gips, *Algorithmic Aesthetics: Computer Models for Criticism and Design in the Arts*. Berkeley, CA, USA: University of California Press, 1978.
[21] L. Zadeh and C. Desoer, *Linear System Theory: The State Space Approach*. Mineola, NY, USA: Courier Dover, 2008.
[22] J. D. Hamilton, "State-space models," *Handbook Econometrics*, vol. 4, pp. 3039–3080, Jan. 1994.
[23] G. Stiny, *Pictorial and Formal Aspects of Shape and Shape Grammars and Aesthetic Systems*. Los Angeles, CA, USA: University of California, 1975.
[24] J. S. Gero, S. J. Louis, and S. Kundu, "Evolutionary learning of novel grammars for design improvement," *Artif. Intell. Eng. Design, Anal. Manuf.*, vol. 8, no. 2, pp. 83–94, 1994.
[25] D. A. Al-Kazzaz and A. H. Bridges, "A framework for adaptation in shape grammars," *Design Stud.*, vol. 33, no. 4, pp. 342–356, 2012.
[26] I. D. Rowland and T. N. Howe, *Vitruvius:'Ten Books on Architecture*. Cambridge, U.K.: Cambridge Univ. Press, 2001.
[27] G. Stiny and O. Y. Gün, "An open conversation with George stiny about calculating and design," *Dosya, Comput. Design*, vol. 29, pp. 6-11, Jan. 2012.
[28] E. Adelson, "Checker shadow illusion," Massachusetts Inst. Technol., Cambridge, MA, USA, Tech. Rep., May 2005.
[29] D. Massaro, F. Savazzi, C. Di Dio, D. Freedberg, V. Gallese, G. Gilli, and A. Marchetti, "When art moves the eyes: A behavioral and eye-tracking study," *PLoS ONE*, vol. 7, no. 5, May 2012, Art. no. e37285.
[30] G. Vittorio, "Neuroaesthetics: A review," *Current Opinion Neurobiol.*, vol. 19, no. 6, pp. 682–687, 2009.
[31] A. Chatterjee, "Neuroaesthetics: A coming of age story," *J. Cognit. Neurosci.*, vol. 23, no. 1, pp. 53–62, Jan. 2011.
[32] M. T. Pearce, D. W. Zaidel, and O. Vartanian, "Neuroaesthetics: The cognitive neuroscience of aesthetic experience," *Perspect. Psychol. Sci.*, vol. 11, no. 2, pp. 265–279, 2016.
[33] A. Chatterjee and O. Vartanian, "Neuroaesthetics," *Trends Cogn. Sci.*, vol. 18, no. 7, pp. 370–375, 2014.
[34] O. Vartanian and A. Chatterjee, "The aesthetic triad," in *Brain, Beauty, and Art: Essays Bringing Neuroaesthetics Into Focus*, vol. 27. London, U.K.: Oxford Univ. Press, 2021.
[35] K. Iigaya, J. P. O'doherty, and G. G. Starr, "Progress and promise in neuroaesthetics," *Neuron*, vol. 108, no. 4, p. 594, 2020.
[36] A. Chatterjee and O. Vartanian, "Neuroscience of aesthetics," *Ann. New York Acad. Sci.*, vol. 1369, no. 1, pp. 172–194, 2016.
[37] N. Motalebi, J. P. Duarte, and J. Pinto, "A shape grammar of emotional postures," in *Proc. eCAADe*, 2017, p. 485.
[38] K. Koffka, *Principles of Gestalt Psychology Harcourt*. Evanston, IL, USA: Routledge, 1935.
[39] M. Wertheimer, "Laws of organization in perceptual forms," in *A Source Book of Gestalt Psychology*, W. D. Ellis, Ed. Kegan Paul, Trench, Trübner & Company, pp. 71–88.
[40] J. J. Koenderink, A. J. Van Doorn, and A. M. Kappers, "Surface perception in pictures," *Perception Psychophysics*, vol. 52, no. 5, pp. 487–496, 1992.
[41] Y. Xu and M. M. Chun, "Visual grouping in human parietal cortex," *Proc. Nat. Acad. Sci. USA*, vol. 104, no. 47, pp. 18766–18771, 2007.
[42] J. J. Koenderink and A. J. van Doorn, "Surface shape and curvature scales," *Image Vis. Comput.*, vol. 10, no. 8, pp. 557–564, Oct. 1992.
[43] G. J. Van Tonder, M. J. Lyons, and Y. Ejima, "Visual structure of a Japanese zen garden," *Nature*, vol. 419, no. 6905, pp. 359–360, 2002.
[44] S. E. Palmer, *Vision Science: Photons to Phenomenology*. Cambridge, MA, USA: MIT Press, 1999.
[45] E. Brattico, "From pleasure to liking and back: Bottom-up and top-down neural routes to the aesthetic enjoyment," in *Art, Aesthetics, and the Brain*. London, U.K.: Oxford Univ. Press, 2015, p. 303.
[46] J. L. Aróstegui, R. Stake, and H. Simons, "Music education for the 21st century: Epistemology and ontology as bases for student aesthetic education," *Educ. Policy Anal. Arch.*, vol. 12, p. 54, Sep. 2004.
[47] P. E. Van Der Vet and N. J. Mars, "Bottom-up construction of ontologies," *IEEE Trans. Knowl. Data Eng.*, vol. 10, no. 4, pp. 513–526, Aug. 1998.
[48] N. Silins, "Cognitive penetration and the epistemology of perception," *Philosophy Compass*, vol. 11, no. 1, pp. 24–42, Jan. 2016.
[49] P. Brey, "The epistemology and ontology of human–computer interaction," *Minds Mach.*, vol. 15, nos. 3–4, pp. 383–398, 2005.
[50] B. R. Conway and A. Rehding, "Neuroaesthetics and the trouble with beauty," *PLoS Biol.*, vol. 11, no. 3, Mar. 2013, Art. no. e1001504.

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