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Neuroaesthetics: a narrative review of neuroimaging techniques

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Abstract
As a new discipline, neuroaesthetics has developed rapidly to become an important branch of neuroscience. The study of neuroaesthetics is of great significance to understanding the mechanisms underlying human aesthetics. In this review, we briefly define neuroaesthetics, and then review the current state of aesthetics research with a focus on single-modal and multi-modal neuroimaging technologies using the visual and auditory modalities. Finally, we summarize current challenges and trends in the field.

Keywords: aesthetics, brain mechanism, cognitive science, neuroaesthetics, neuroimaging

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Introduction

Beauty has been a topic of curiosity since antiquity, and has been considered by many great philosophers (eg, Plato, Kant, and Hume on aesthetics).[1] Fechner was a German esthetician who was the first to apply natural scientific methods in aesthetic research.[2] He proposed "bottom-up" experimental aesthetics, which laid the necessary foundation for a cognitive approach to aesthetic research. Based on this idea, subsequent researchers began to study the internal mechanisms of aesthetic activities from the perspective of cognitive psychology and neuroscience.[3] The anatomical structure of the neural system and the principles that guide neurological activity are inseparable from the processes and mechanisms underlying aesthetic cognition. Zeki et al[4] realized the importance of neural mechanisms in the field of aesthetics, and began to study the relationship between the brain and art. They first proposed the concept of neuroaesthetics, defined as the study of the neural basis of the creation and appreciation of art. Subsequently, Hansen et al[5] published the first study on neuroaesthetics, in which they explored visual preferences for artistic pictures. This was followed by a study by Vartanian et al,[6] who explored the neuroanatomical correlates of aesthetic preferences in painting. They found that activation in the right caudate nucleus decreased in response to decreased preference, and that activation in the bilateral occipital gyri, left cingulate sulcus, and bilateral fusiform gyri increased in response to increased preference. At the same time, Cela et al[7] reported the results of a magnetoencephalography experiment, which showed that the prefrontal area was selectively activated in humans during the perception of objects qualified as "beautiful" by the participants. These findings indicate that aesthetics can be considered as an attribute perceived by means of a specific brain processing system, in which the prefrontal cortex seems to play a key role.

Nadal[8] believes that studies of neuroaesthetics should consider the "aesthetic attitudes" with which people experience various objects. Therefore, he defines neuroaesthetics as the neural mechanisms underlying the mental activities that occur when viewing objects. These mental activities (including perception, emotion, evaluation, and other social aspects) are the psychological functions of the human body, which depend on corresponding neural structures. In understanding aesthetics from a biological perspective, Chatterjee believes that aesthetic experience comes from the interaction of three nervous systems: the sensory-motor system, the emotion-evaluation system, and the knowledge-meaning system.[8] Different mental activities in each system activate different brain areas. Ishizu et al[9] showed that the medial orbitofrontal cortex (mOFC) may be involved in most aesthetic experience. Further, in a meta-analysis by Brown et al,[10] the researchers suggested that the right anterior insula is activated during all aesthetic experiences, and that different parts of the orbitofrontal cortex (OFC) are implicated in different types of aesthetic experiences, such as those centered on taste, smell, sight, and audition. Beauty is deeply encoded in the brain, and that external stimulation can cause a series of changes in the cerebral cortex. In-depth exploration of the neurological mechanisms of aesthetics will help uncover the mystery of beauty.

Objective

Neuroaesthetics has become an independent research field in less than two decades, with the goal of examining aesthetics from the perspective of neurobiology. The rapid development of cognitive neuroscience has provided a scientific basis for research on aesthetics. In the following sections, we first review neuro-aesthetic research conducted using neuroimaging, and then summarize existing challenges and propose future development trends.

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Database search strategy

The authors used the following inclusion criteria: studies that discussed the neural response caused by aesthetic activities. Literature review was electronically performed in PubMed database. Most of the selected studies (80% of all references) were published from 2010 to 2019. An ancient publication from 1998 was included in consideration to its relevance in the neuroaesthetic field. The following combinations of keywords were used for initial literature search: aesthetic, neuroaesthetic, beauty, electroencephalography (EEG), functional magnetic resonance imaging (fMRI), positron emission tomography (PET), magnetoencephalography (MEG), etc. The authors screened the titles and abstracts, and then the full texts for keywords to find those that were potentially suitable.

Aesthetic research conducted using neuroimaging technology

Non-invasive neuroimaging techniques, such as EEG, fMRI, PET, and MEG, are frequently combined with paradigms commonly used in experimental aesthetics research. In these studies, brain activity is recorded and analyzed while participants make judgments regarding the degree of preference for presented stimuli. Neuroimaging technologies are powerful tools for examining brain mechanisms, especially those underlying advanced cognitive activities such as learning, thinking, language, memory, and emotion. In this section, we review recent aesthetic studies conducted using single technologies such as EEG, fMRI, and MEG, as well as those conducted using multimodal hybrid technologies.

Research conducted using EEG/MEG/fMRI

Paintings and faces have received extensive attention in current aesthetics research as important sources of visual aesthetic information. Prior to the development of the field of neuroaesthetics, Zeki et al[11] found that human visual cognition, color processing, and motor feature detection are not carried out in parts of the primary visual cortex such as V1, V2, and V3, but occur in the joint cortex (V4, V5) and the orbitofrontal cortex of the prefrontal lobe. This shows that the prefrontal lobe plays an important role in human visual processing. The findings from the first study on the neurobiological response to viewing artworks such as paintings and sculptures clearly indicated that the brain activities involved are not only related to the occipital lobe, but also involve more complex visual processing.[10] In a study by Kawabata et al,[12] participants were asked to make aesthetic judgments about abstract, landscape, portrait, and still life paintings, and to identify them as ugly, neutral, or beautiful. The results of fMRI scans showed that activity in the orbitofrontal cortex increased with the perceived degree of beauty, while activity in the motor cortex showed the opposite pattern. This result suggests that the orbitofrontal cortex and motor cortex may be specific regions involved in processing aesthetic information. Similarly, the findings of Vessel et al[13] indicated that the occipitotemporal region, striatum, and frontal region may be implicated in the aesthetic evaluation of paintings.

Most studies that we evaluated used MEG and EEG techniques, which have a high temporal resolution, to explore brain activity that occurred when participants were asked to evaluate a painting. In the Cela-Condet et al[7] study, participants judged whether the stimulus is beautiful. After analyzing the recorded MEG signals, they found that compared to stimuli that are judged to be unbeautiful, the beautiful caused heightened activity in the left prefrontal dorsolateral cortex in 400–900 ms, which is consistent with the results of Munar et al.[14] Kim et al[15] found that compared with images containing no text information, ERPs elicited by images containing text information had more variations, indicating that the brain processed more visual information when multiple forms of stimuli were presented simultaneously. Many studies have explored the neural mechanisms underlying the aesthetics of paintings, using various perspectives. Although the results of these studies have had some variations, the brain areas implicated in painting aesthetics have mainly been found to be related to visual information, as well as cognitive and emotional processing.

Faces are another focus of visual aesthetics research, as the attractiveness of appearance may be a factor that affects fertility and genetic quality. Faces are generally thought to reflect visual attractiveness. Physical features such as averageness and symmetry are consistently considered to be important elements of facial attractiveness.[16] Evolutionarily, physical attractiveness could communicate information about fertility and gene quality, and faces, as an important component of appearance, have attracted extensive attention from aesthetics researchers. The mOFC is thought to be the main brain area implicated in face aesthetics. O'Doherty et al[17] explored the neural response to facial attractiveness in participants of different genders, and found that compared with neutral faces and unattractive faces, attractive faces elicited significantly more mOFC activity, regardless of the gender of the viewer. In a recent study, Pegors et al[18] found that the lateral OFC was selectively activated for facial beauty over landscape beauty, indicating that the brain has different systems (ie, different areas) for general and attractiveness-specific face aesthetics. Brain responses to attractive faces are produced by interactions between multiple factors. Several fMRI studies have shown that attractive faces can cause positive emotional reactions, indicating that judgments of attractiveness are related to many structures involved in evaluation judgments or reward processing, including the nucleus accumbens and dorsal striatum.[17,19] In a study by Luo et al,[20] participants were asked to make general aesthetic judgments about both faces and moral descriptions. The results showed that the appreciation of facial and moral beauty activated a common brain region, which included the middle occipital gyrus (MOG) and mOFC. Activity in the mOFC has been found to vary under different aesthetic conditions, while the MOG is specifically activated only when stimuli are perceived to be beautiful. These results provided novel neurological evidence for a theory of integrated aesthetics, where integrated aesthetics relies on more complex cognitive processes compared with aesthetics (when limited to a single form). As other characteristics are known to affect the judgment of facial attractiveness, some researchers examined the influence of other characteristics, such as body appearance. In a recent fMRI study,[21] images of faces and bodies were presented to participants. The results showed that activity in the nucleus accumbens and anterior cingulate cortex increased with increased ratings of attractiveness for both faces and bodies. However, other areas, such as the anterior cingulate cortex, posterior cingulate cortex, middle cingulate cortex, and the mOFC, exhibited nonlinearity. These data provide information regarding the visual processing related to physical characteristics and form an effective basis for exploring the neural preferences generated by natural stimuli such as faces and bodies.

In addition to stimulating materials (such as faces or paintings), different factors of the subjects themselves (such as knowledge background, educational level, and mental state) will also affect the process of aesthetic appreciation. In an fMRI study, Kirk et al[22] explored the aesthetic differences between normal background and abnormal background images. Their results showed that regardless of whether or not the background was normal, aesthetic judgments activated the mOFC and the lateral OFC. In another study, the labels of paintings were found to affect aesthetic judgments. The researchers randomly labeled the same batch of paintings as "from the museum" or "synthesized by a computer." Participants rated the paintings with the "from the museum" label as being more aesthetically pleasing, and activation of the mOFC was significantly higher for these paintings compared with those with the "synthesized by a computer" label.[22] Cela-Condeat et al[23] explored the influence of gender on aesthetic judgments and found that for paintings judged by the subjects as beautiful, there were significant gender differences in activity in the parietal region. Specifically, women exhibited activation in both hemispheres, while men only showed activation on the right side.

However, whether the brain mechanisms involved in visual aesthetic stimulation are similar to those for other sensory pathways is not clear. Are there specific brain regions that correspond to different stimulus pathways that control aesthetic activity? An fMRI study conducted by Ishizu et al[24] indicated that activation in the mOFC was enhanced both when listening to beautiful music and when viewing beautiful paintings, suggesting that the mOFC may be a specific brain area responsible for aesthetic processing. To address this, researchers have examined auditory aesthetics using music as a stimulus material.

As research in the field of neuroaesthetics has progressed, several brain regions have been related to auditory pleasure. These were involved in the emotion prediction and emotion reward experience of the listener. Arikan et al[25] found that the amplitude of the P3 ERP component increased significantly when subjects listened to familiar music. The P3 component reflects the top-down processing of information, which involves the prefrontal lobe. After studying the neural responses of music experts and non-experts while they listened to music, Müller et al[26] found that experts produced a stronger amplitude of the ERP component contingent negative variation (CVN) in aesthetic judgments. Non-expert judgments of beauty, as reflected by the brain activity at the sound of the last chord of the piece of music, were accompanied by a greater late positive potential (LPP), indicating that their aesthetic judgments were more dependent on inner emotional state compared with experts. Using PET, Salimpoor et al[27] found that the nucleus accumbens of the striatum was significantly activated when listeners rated music as enjoyable compared with the unpleasant music, which may have been accompanied the release of endogenous dopamine. Therefore, activity in the nucleus accumbens may reflect the pleasure of listening to a piece of music for the first time. Later, Salimpoor et al[28] found that when subjects were listening to a piece of music that they had not previously heard, the level of neural activity in the nucleus accumbens was linearly correlated with the degree of preference for the music. Thus, the nucleus accumbens may integrate sensory information from the amygdala, thalamus, auditory cortex, and other parts of the brain, and then play a role in value judgments conducted according to aesthetic ideals and expectations.

However, not everyone likes to listen to pleasant music. For some people, sad music can resonate strongly. Koelsch et al[29] found that the left contralateral amygdala had a highly specific sensitivity to pleasant music, while the right basolateral amygdala was activated during sad music. Why do some people like to listen to sad music? Is the neural mechanism consistent with that underlying the appreciation of pleasant music? Kawakami et al[30] found that subjects felt more satisfied when listening to sad music compared with happy music, similar to the results reported by Sloboda et al[31] The feelings elicited by listening to sad music could be considered as "substitute emotions," where emotions are not generated by real-life events. Further, positive emotions may be derived from the similarities between sadness and pleasure. Regardless of the type of music, people are likely to have different aesthetic experiences based on their own emotions. Table 1 summarizes the principal experimental tasks and results of the main aesthetic studies using visual and auditory perception.

From the above research, it appears that aesthetic experiences caused by different sensory stimuli can cause corresponding neural responses. At the same time, various factors such as gender, environment, and background knowledge can cause aesthetic differences. Further research using neuroimaging is necessary to illuminate the mechanisms related to aesthetic processing and promote the development of aesthetic research.

Research using multi-mode hybrid technology

Aesthetic activities generally start with perception and end with emotion. Perception and emotion are both important components of cognitive activity, and their functions depend on the corresponding neural structures, which involve different sensory and processing systems. With the development of signal acquisition technology, a variety of physiological signals have been used as an objective way to understand perception. These techniques include skin conductance variability,[32] eye trackers,[33] EEG, and fMRI.[34] Eye-tracking is an eye sensor technology in which attention or other mental states are inferred from eye position data, offering insight into individual aesthetic activities. Studies have found that pupil size, as one variable measured using eye tracking, is related to aesthetic preferences regarding artworks.[35,36] For instance, Ho and Lu[37] found that the index of pupil size could be used to distinguish different degrees of aesthetic stimulation, indicating that pupil size was related to aesthetic activities. Specifically, when the degree of arousal was high, the participants attended to an image of an unpleasant scene for longer than an image of a pleasant scene, while the opposite was observed when the degree of arousal was low.[38] In addition, fixation was more frequent for pleasant images than for unpleasant images.[39] However, these studies all used single-modal physiological signals to measure aesthetics. To comprehensively analyze and understand aesthetic activities, the integration of multiple physiological signals is likely to be beneficial.

Graphics and text elements are aesthetic attributes that can be examined using modern neurotechnology. In 2015, Rojas et al[40] combined EEG technology with eye-tracking technology to evaluate the visual perception of products. Participants made judgments regarding the consistency of a semantic description and image for packaging designs stimuli. The results showed a relationship between adjectives, packaging design attributes, and specific visual elements, providing an objective basis for the optimization of product design.

Constrained by the limitations of technology, many aesthetic studies are conducted in laboratory environments, where stimuli are presented on computer screens. However, in recent years, new developments have made it possible to collect physiological

Table 1

Overview of some of the main aesthetic studies that used visual and auditory stimuli

Authors	Methodology	Description	Major results
Paintings			
Kawabata et al[12]	fMRI, paintings	Each subject viewed paintings and classified them into beautiful, neutral, or ugly	The orbito-frontal cortex is differentially engaged during the perception of beautiful and ugly stimuli, regardless of the category of painting.
Munar et al[14]	MEG, images	Ten women and men volunteered to judge the image "beautiful" or "no beautiful."	Event-related field revealed no significant differences between "beautiful" and "not beautiful." Time-Frequency analysis showed clear differences between both conditions 400ms after stimulus onset.
Kim et al[15]	EEG, images	Two oddball tasks were performed for general images and signboard images including text stimuli	The change of ERP in signboard image was larger than that of general image.
Face			
O'Doherty et al[17]	fMRI, faces	To investigate brain regions that respond to attractive faces.	Attractive faces produced activation of mOFC.
Pegors et al[18]	fMRI, faces and places	Participants made attractiveness judgments of faces and places.	Ventromedial prefrontal cortex supports a common mechanism, whereas lateral OFC may be involved in basic reward processing.
Luo et al[20]	fMRI, facial and moral beauty	Participants were asked to make general aesthetic judgments of facial portraits and moral descriptions.	The activities of the mOFC varied across aesthetic conditions, while the middle occipital gyrus was specifically activated in the most beautiful condition.
Other influencing factors			
Kirk et al[21]	fMRI, images with different contextual	To investigate the relationship between aesthetic judgment and images in their normal contextual vs. abnormal contextual settings.	Medial and lateral aspects of the orbitofrontal cortex were activated, while visual cortical areas recruited in normal contexts.
Music			
Müller et al[26]	EEG, music	16 music experts and laypersons judged the aesthetic value as well as the harmonic correctness of chord sequences.	During the interval of task-cue presentation, a stronger contingent negative variation to the beauty judgment task was observed for experts.
Salimpoor et al[27]	PET/fMRI, music	Participants were asked to listen to music	The caudate was more involved during the anticipation and the nucleus accumbens was more involved during the experience of peak emotional.
Koelsch et al[29]	fMRI, music	To investigate the brain correlates of music-evoked emotions	The left contralateral amygdala had a highly specific sensitivity to pleasant music, while the right basolateral amygdala had a response to the sad one.
Kawakami et al[30]	Behavior	Participants listened to music and rated descriptive words or phrases related to emotions.	The actual experiences of the participants listening to the sad music induced them to feel more romantic, and less tragic emotions than they perceived with respect to the same music.

EEG = electroencephalogram, fMRI = functional magnetic resonance imaging, MEG = magnetoencephalography, mOFC = medial orbitofrontal cortex, OFC = orbitofrontal cortex, PET = positron emission tomography.

signals from freely moving subjects. For instance, Babiloni et al[41] collected EEG data and eye activity signals from healthy subjects while they viewed paintings in an art gallery. The result indicated that the number of eye fixations and the total number of fixations in the first 10 seconds were significantly higher when viewing favorite versus disliked paintings. Further, the approach-withdrawal (AW) index in the first 20 seconds of viewing was highly correlated with the EEG data in a later time period, indicating that the perception of "beauty" or "unbeauty" of the painting was generated within 10 to 20 seconds from the beginning of viewing. In a recent study, Yang et al[42] combined EEG and eye movement data to optimize a user interface design, and demonstrated the feasibility of the proposed method for aesthetic design processes. Guo et al[34] designed a 3D model of a LED desk lamp with the goal of simulating the aesthetic appreciation process. After analyzing EEG and eye movement data, the researchers found that the average fixation duration significantly differed only between lamps with low and high aesthetic appeal, and they found no significant variations in pupil size. Moreover, the relative power of brain oscillations in the alpha band elicited by viewing the table lamp with a low aesthetic rating was significantly reduced, while the power in the gamma band was significantly enhanced. Thus, the combination of EEG and eye trackers has potential for examining the neural basis of various cognitive functions, and, such as in the above case, could facilitate more intuitive design decisions.

Although many aesthetics studies have used fMRI, the low temporal resolution, negative ecological effects, and restricted environment limit its practical applications. To investigate the spatiotemporal dynamics of the brain regions and networks involved in aesthetic activity, some researchers have used combined EEG and fMRI to explore neural responses to visual stimuli. For instance, Sabatinelli et al[43] combined EEG and fMRI to analyze slow-wave LPP and blood oxygen level-dependent (BOLD) signals when viewing different types of images. They found that LPP amplitude was significantly correlated with the BOLD intensity in the lateral occipital, inferotemporal, and medial parietal cortex, indicating that the enhanced LPP in the posterior cortex during image processing represented activity in the visual cortex. Schelenz et al[44] proposed a method to study the neural correlation of electrophysiological oscillations during the integration of multisensory stimuli. Stimulus materials include audity, visual and audiovisual blocks, and subjects respond to the stimuli. The results suggested that alpha oscillations were suppressed in the bilateral occipital cortices in the early time window after stimulus onset, while fMRI data showed reliable activation elicited by multisensory stimuli in auditory, visual, and frontal areas. In addition, a reliable correlation pattern between occipital event-locked α inhibition and the BOLD signal time course has provided an effective approach for EEG-fMRI research. In a recent study, Moore et al[45] used fMRI and EEG to examine the spatiotemporal dynamics of neural processing in the emotional oddball paradigm. The results showed that the LPP amplitude in the parietal lobe and the fMRI signal from the ventrolateral prefrontal cortex were modulated by different types of images, indicating that the dorsal executive neural system is involved in attention and executive functions associated with target-related processes. These results highlight complementarity between techniques for capturing the spatiotemporal dynamics of brain activity, making them effective methods for comprehensively investigating individual differences in the aesthetic and attention domains. The integration of multimodal physiological signals can compensate for the limitations of single technique measurements, as well as lead to an improved aesthetic evaluation standard.

Summarizing the above research, the application of multimodal technology in the study of neuroaesthetics is likely to lead to a more comprehensive understanding of the neural activity underlying an aesthetic experience. However, the acquisition of multi-modal physiological signals and corresponding data processing can be challenging, making it is particularly important to optimize the experimental design.

Challenges and developing trends

Developments in the field of neuroaesthetics have produced new information regarding the neural mechanisms of aesthetic and artistic activities. However, many challenges and opportunities remain.

First, the experimental materials in the existing research have centered on paintings, faces, and music, and few studies have examined work in other artistic categories, such as movies, literature, and dance. Further, most stimuli have been based on Western artforms, and few studies have examined artwork with Chinese characteristics. Therefore, in future research, more effort should be devoted to exploring neural activity elicited by artworks from non-Western regions. Further, the inclusion of different types of art will enable a more comprehensive understanding of the neural basis of aesthetic appreciation through different sensory channels. Future work could examine the aesthetics of traditional Chinese painting, Tang poetry, Chinese courtyard landscapes, and other art forms.

Second, few studies have examined aesthetic experiences in individuals with psychological conditions (such as depression or autism). Understanding the neural mechanisms of aesthetic activity in specific populations may lead to customized forms of art therapy for these groups. Moreover, most studies have taken place in a laboratory environment, which cannot provide participants with an immersive aesthetic experience. New technologies may lead to more realistic experimental environments, as well as enhanced options for wearable devices.

Third, the development of neuroaesthetics has largely benefited from advancements in neuroimaging technology. However, each form of neuroimaging technology has advantages and disadvantages, such as the high (low) temporal resolution and low (high) spatial resolution of EEG (fMRI) technology. Few studies have examined the dynamic processes associated with cognitive and emotional processing during aesthetic activity. Therefore, multimodal technologies (such as fMRI and EEG or skin electromyography and EEG) may be used to explore neural activity from a more comprehensive perspective, to better understand the subtle differences in neural responses during aesthetic experiences.

Neuroaesthetics is an important branch of neuroscience. Although many challenges remain, these are accompanied by new opportunities to deepen our understanding of how the human brain supports artistic evaluation and appreciation.

Limitations

This paper has some limitations. It only reviews aesthetics in terms of experimental design and engineering technology but does not provide a profound explanation of aesthetics theory. No in-depth explanation of the processing method of aesthetic data. And there is no comprehensive review of the research progress of contemporary aesthetics (for example, lack of oriental art aesthetics).

Conclusion

More research is needed regarding the human physiological mechanisms that underlie aesthetic perception. Non-invasive brain imaging technology can be used to examine the cognitive processes associated with complex aesthetic phenomena. Various research methods and experimental designs have revealed elements of neural aesthetic processing from different perspectives. Future scientific exploration of aesthetics is expected to overcome existing development bottlenecks, greatly promoting our understanding of the neural mechanisms behind aesthetic activities.

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Author contributions

ZC, XY, WL conceptualized this work. ZC drafted the manuscript. LW revised the manuscript. WL provided the funding. All authors approved the final version of the manuscript.

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Conflicts of interest

None of the authors are the Editorial members of the *Journal of Bio-X Research*.

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