Title of Thesis

Study on Neural Mechanisms of Attention Effects on Auditory-Tactile Multisensory Processing

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Abstract

This study focuses on understanding the impact of attention on auditory-tactile integration. Multisensory integration refers to the process by which information from different sensory modalities (e.g., vision, hearing, touch, smell, taste, etc.) is combined, coordinated, and interacts in the nervous system to form a unified perceptual experience. The occurrence of multisensory integration depends on the coordinated work of multiple brain regions, such as the superior colliculus, the temporoparietal junction, and the prefrontal cortex, as well as the regulation of factors such as the temporal consistency of stimuli, signal strength, and individual experience. This integration process enhances the efficiency of perception of the external environment and improves the accuracy and adaptability of behavioral responses. Multisensory integration is strongly related to attention mechanisms. Attention not only regulates the efficiency of integration but also resolves sensory conflicts and improves signal selection. By using behavioral experiments, neuroimaging techniques (such as fMRI, EEG, and MEG), and multimodal analysis methods, the neural mechanisms and dynamic characteristics of multisensory integration can be revealed in depth. However, most of the current research on multisensory integration focuses on the integration of visual and auditory modalities. The brain mechanisms of auditory-tactile multisensory processing and how this process is influenced by factors such as attention are still unclear. To this end, we designed an experiment to investigate the influence of attention on auditory-tactile integration from three perspectives: behavioral, time-related potentials, and time-frequency analysis.

First, we investigated whether auditory-tactile can be integrated. Previous research on auditory-tactile integration does not provide a clear conclusion as to whether auditory-tactile integration can occur in both the left and right-hemispheric space of the body, or whether there are differences in auditory-tactile integration between these two sides. Therefore, we used behavioral data to analyze the reaction time, accuracy, and race model of the participants' responses to stimuli from each modality in different spatial locations. The results showed that for stimuli presented in the left and right hemispaces, participants' reaction times to bimodal stimuli were significantly faster than those to unimodal stimuli, and the accuracy of responses to bimodal stimuli was also higher than that to unimodal stimuli. In addition, race model analysis showed that when the stimulus was presented in the left hemispace, auditory-tactile integration occurred earlier and had a wider time range. Specifically, for stimuli in the left hemispace, the integration effect was found 368 milliseconds after the stimulus and lasted until 594 milliseconds after the stimulus. For stimuli in the right hemispace, the integration effect was observed 407 milliseconds after stimulus onset and ended at 594 milliseconds. These findings indicate that auditory-tactile integration can occur in both the left and right hemispaces of the body, and that the integration effect is influenced by the location of stimulus presentation.

Then, we explored the spatiotemporal distribution of auditory-tactile integration under different conditions. To do this, we calculated event-related potentials for different stimulus types under different conditions. Integration was quantified by comparing the response to a combined stimulus to the sum of the responses to the auditory and tactile stimuli presented separately. The ERP results showed that when the stimulus was presented in the left hemispace, auditory-tactile integration occurred earlier under the attended condition, and integration was found as early as in the 70-90 ms, and the integration effect appeared in a wider range of brain regions. While integration was found only in the 180~220 ms time window in unattended condition. When stimuli were presented in the right hemispace, auditory-tactile integration occurred earlier in the unattended condition, as early as 110 to 130 ms, and the integration effect occurred over a wider range of brain regions, whereas in the attended condition integration was found only in 180 to 220 ms. Overall, auditory-tactile integration occurred earlier and was more extensive for stimuli presented in the left hemispace. These results suggest that attention can modulate auditory-tactile integration and that this modulation is influenced by the location of stimulus presented. These findings contribute to the understanding of the mechanisms of auditory-tactile information processing in the human brain.

Finally, we explored the interaction between auditory-tactile integration and attention using gamma-band neural oscillations. Gamma-band responses are associated with attention and perceptual integration, and analyzing gamma-band responses is a useful tool for investigating the processes by which attention influences multisensory integration. Previous studies showed that multisensory stimuli elicited stronger gamma-band responses than unisensory stimuli in central, parietal, and occipital brain regions. In addition, attended auditory and visual stimuli produce stronger gamma-band responses than unattended stimuli. Therefore, we analyzed the relationship between multisensory integration and attention through gamma-band responses. The results showed that when the stimuli were presented in the left hemispace, the effect of auditory-tactile integration in the attended condition was significant. When the stimuli were presented in the right hemispace, the effects of auditory-tactile integration were significant in the unattended condition. These findings suggest that the effects of attention on auditory-tactile integration were modulated by the location of stimulus presented.

In summary, auditory-tactile multisensory stimuli can be integrated in both the left and right hemispaces. Furthermore, attention and the spatial location of stimulus presented significantly affect the temporal dynamic and brain activation pattern of auditory-tactile integration. Specifically, in the left hemispace, the auditory-tactile integration effect was stronger under the attended condition, while in the right hemispace, the auditory-tactile integration effect was stronger under the unattended condition.

Keyword: auditory–tactile integration; selective spatial attention; ERPs; left–right hemispace differences; gamma-band neural oscillations

Content

1. Introduction

1.1. Multisensory integration definition and expression

Multisensory integration refers to the process by which the brain combines and synthesizes information from different sensory modalities (visual, auditory, tactile, etc.) to form a more complete, accurate, and consistent perceptual representation of the external world[1-3]. This process is crucial for improving perceptual efficiency, enhancing spatial orientation and object recognition, facilitating social communication, and supporting flexible behavioral decision-making[4,5]. There are two main forms of multisensory integration. The first is multisensory illusion, such as the McGurk effect. When the audience sees someone’s, lips moving but the sound they hear doesn't match, the brain will create a mixed perception, causing the syllables the audience hears to be “rewritten”. For example, in a video where the actor's lips look like they are pronouncing “ga” but the sound is playing “ba”, the audience will perceive the sound as “da” or “tha”. Another is multisensory facilitation, such as the redundant signal effect. When we pick up a keychain, we quickly recognize it as a “key” based on its texture, metallic sound, and shape. Information from multiple sensory modalities allows us to identify objects more accurately and quickly.

1.2. Neural mechanisms of multisensory integration EEG

1.2.1. Primary sensory cortex information preprocessing

Multisensory processing involves multiple brain regions. Before multisensory integration occurs, information from different modalities is first projected separately to their respective primary sensory cortices for necessary “preprocessing” and feature extraction. The visual cortex (V1) is responsible for the separation and detection of visual features such as color, shape, and movement [6]. The auditory cortex (A1) mainly analyzes the frequency, loudness and temporal characteristics of sounds. The somatosensory cortex (S1) processes signals such as tactile, temperature, pain and somatosensory awareness [7]. The vestibular system provides information about head position, acceleration and body balance[8]. In addition, there is some cross-modal modulation between primary sensory cortices[6]. However, large-scale and significant integration is generally thought to be found in the association cortices and critical subcortical structures [3,9].

1.2.2. Multisensory integration in the association area

After primary processing, information from different sensory modalities is transmitted to the relevant multisensory association areas for integration [10]. Critical brain regions include the superior temporal sulcus, the temporo-parietal association area, and the parieto-occipital association area. The superior temporal sulcus plays an important role in the integration of social cues such as facial expressions, speech, and movement [1,2]. The temporo-parietal association area is closely related to body space perception, self-awareness, and attention switching[4]. It can integrate information from visual, auditory, vestibular and somatosensory perception to help an individual determine the position of the body in space. The parietal association area specializes in the integration of visual-somatosensory information and contributes to spatial orientation and movement planning[7]. When an individual grasps and manipulates an object, the parietal area combines visual spatial information with somatosensory information to precisely adjust hand-eye coordination.

1.2.3. Superior colliculus in multisensory integration.

Subcortical structures also play an important role in multisensory integration. The superior colliculus can integrate positional information from visual and auditory (and even tactile) cues to guide individuals in rapid orientation behaviours such as head turning, eye rolling or escaping [2]. Subcortical structures also play an important role in multisensory integration. The superior colliculus can integrate positional information from visual and auditory (and even tactile) cues to guide individuals in rapid orientation behaviours such as head turning, eye rolling or escaping [2]. When multiple modality stimuli are temporally and spatially matched, neurons in the superior colliculus show cross-modal enhancement; if they are mismatched, the enhancement weakens or even disappears [10,11]. Early and rapid multisensory information integration via the superior colliculus is important for survival behaviors such as predation or avoiding danger [2].

1.2.4. Multisensory integration across brain regions

Multisensory integration not only relies on specific brain regions but also involves a networked process across regions and layers[1,3]. Multisensory integration not only relies on specific brain regions but also involves a networked process across regions and layers[3]. Studies have found that information is effectively coupled in time and space between different brain regions through neural oscillations and brain region synchronization[6]. Synchronization in the gamma band (approximately 30-100 Hz) is often regarded as a critical mechanism for cross-modal feature binding, which helps integrate information from different modalities over time [12]. Synchronization between different brain regions may coordinate long-range information transmission via lower frequency rhythms such as theta or beta bands[9].

1.3. Attention affects multisensory integration

In daily life, individuals are simultaneously exposed to a vast amount of information from multiple sensory modalities, including visual, auditory, tactile, olfactory, gustatory, and vestibular senses. The brain has to integrate and process useful information within a very short period of time to guide adaptive behaviors[1,2]. The attention mechanism plays a key “filtering” and “amplifying” role in this process: it can selectively focus on or inhibit specific sensory inputs with limited cognitive resources, thereby affecting the efficiency and results of multisensory integration[3,4].

In multisensory contexts, selective attention can significantly alter the perception and processing depth of different sensory information. For example, in a noisy environment, people can “focus” on the speaker's mouth shape and voice, thereby enhancing the understanding of the speech content[4]. On the contrary, if attention is distracted or interfered with by other stimuli, the integration effect of visual and auditory information will be greatly reduced [9]. When visual mouth shapes and auditory speech do not match, people experience “mixed perception”, which is usually stronger under conditions of high concentration[13]. The McGurk effect may be weakened if an individual takes their attention away from the speaker's mouth shape, indicating that attention plays an important role in the process of “binding” across sensory integration.

Early research on multisensory integration emphasized bottom-up information integration, but top-down attention regulation is also important[14]. Brain regions such as the prefrontal lobe (e.g., dorsolateral prefrontal cortex) and parietal lobe (e.g., intraparietal and temporoparietal junction) work together to form the prefrontal-parietal network that controls attention [15]. This network transmits feedback signals to the primary sensory cortex and multimodal association areas through neural oscillation synchronization and synaptic connections, selectively enhancing or inhibiting certain sensory inputs[3,7]. The temporo-parietal association area plays a crucial role in shifting attention and processing cross-modal spatial information [4]. The prefrontal cortex is involved in determining the allocation of attentional resources and task demands, generating “expectations” and “instructions” for the next step of integrating goals [15]. In multisensory contexts, attention can influence information integration by altering the oscillatory patterns between different brain regions[16-19]. For example, phase synchronization of gamma-band oscillations in the parietal-frontal network may indicate amplification of target modality information, while activity in the alpha/beta band may be related to suppression of irrelevant or distracting stimuli[20]. These patterns of neural activity also show corresponding dynamic plasticity when an individual's attention strategy or external task demands change, providing a physiological basis for real-time regulation by the brain [21-24]. Under the framework of “predictive coding”, the brain continuously predicts the environment based on prior knowledge and compares it with actual sensory input [25-27]. When a modality is highly relevant to the current task, the brain assigns it more “weight” to reduce prediction errors. If the sensory input is clearly inconsistent with the prediction, it will cause a stronger neural response, prompting the brain to update its internal model or reallocate attention resources [28,29].

Investigating the relationship between attention and multisensory integration is important for clinical and applied purposes. Individuals with poor multisensory integration often have attention deficits. For example, individuals with autism spectrum disorder (ASD) and attention deficit hyperactivity disorder (ADHD) have difficulty in integrating cross-modal information and regulating attention[5]. Specific multisensory training combined with attention interventions can help improve the ability of patients to integrate environmental information. Effective use of multisensory materials and attention training in the teaching environment can improve students' learning performance [30]. Technology such as virtual reality (VR) and augmented reality (AR) is focused on generating realistic multisensory stimuli to make users feel immersed in a “realistic” environment [31,32]. By adjusting the temporal matching of visual, auditory, and tactile channel stimuli and attention cues, researchers can guide users to focus more effectively on target information, thereby enhancing the interactive experience and immersion of the VR/AR system[33-36].

In summary, attention plays a key role as a “modulator” in multisensory integration. It can top-down select, amplify, or inhibit inputs from various senses, thereby directly affecting the efficiency of cross-modal integration[37,38]. On the neural level, attention achieves this goal through feedback mechanisms and neural oscillation synchronization in advanced regions such as the prefrontal and parietal lobes. On the behavioral level, selective attention and cross-modal attention can change the dominant modality and depth of integration, thereby affecting people's judgments, learning, and decision-making about external events. With the rapid development of multimodal brain imaging, brain-computer interfaces, machine learning, and virtual reality technology, future research on “how to effectively use attention in natural contexts to promote or optimize multisensory integration” will receive more attention[39-43]. This will not only enhance our understanding of human cognition but also provide new theoretical insights and practical innovations in educational training, neurological rehabilitation, and the design of human-computer interaction systems.

1.4. EEG

Electroencephalography (EEG) is a non-invasive neuroimaging technique that records the synchronous electrical activity of neuronal populations in the cerebral cortex. It has significant advantages such as high temporal resolution, relatively low cost and portability[44,45]. For a long time, EEG has played an important role in fields such as neuroscientific research, clinical diagnosis, cognitive psychology, and brain-computer interfaces[41,46]. In recent years, with the rapid development of signal processing algorithms, artificial intelligence, and wearable hardware, EEG applications have faced new opportunities and challenges[47-49].

1.4.1. Physiological basis of EEG signals

In general, EEG is considered to be the surface projection of large-scale synchronous activity in the cerebral cortex, involving the superposition of synaptic inputs from neurons, local field potentials (LFPs) and dipoles[50,51]. In this process, pyramidal cells occupy a central position; they generate detectable macroscopic brain electrical signals when the accumulation of postsynaptic potentials reaches a certain level in time and space [52-54]. When pyramidal cells receive synaptic inputs from upstream neurons, subtle changes in membrane potential occur in the dendritic and somatic regions. There are two most common types of postsynaptic potentials: the excitatory postsynaptic potential (EPSP) and the inhibitory postsynaptic potential (IPSP). When an excitatory neurotransmitter such as glutamate binds to a postsynaptic membrane receptor, the membrane potential shifts in the direction of depolarization, that is, closer to the threshold for triggering an action potential. This produces an excitatory postsynaptic potential, making it easier for the neuron to fire. When inhibitory neurotransmitters such as GABA (gamma-aminobutyric acid) bind with the corresponding receptors, the membrane potential shifts towards hyperpolarization, away from the action potential threshold, resulting in an inhibitory postsynaptic potential, which makes it more difficult for the neuron to fire. If only a few neurons or synapses fire, the resulting local membrane potential changes may be extremely weak and insufficient to affect the macroscopic EEG signal. When a large number of neurons depolarize or hyperpolarize in a similar way at the same time, a strong local field potential (LFP) is formed[55].

The local field potential (LFP) refers to the potential distribution caused by extracellular currents generated by changes in neuronal membrane potentials within a certain spatial range. Its amplitude is not merely the contribution of a single synapse but rather the vector summation of hundreds or even thousands of postsynaptic potentials. Similarly, scalp EEG signals can be regarded as a macroscopic projection of large-scale LFPs within the brain. Without large-scale neuronal synchronization, sufficient current summation to penetrate the scalp is difficult to achieve [56]. Thus, LFPs are considered a "mesoscale" neural signal: larger than the membrane potential of individual neurons but smaller than the overall oscillations spanning large cortical areas. The classic EEG frequency bands (δ, θ, α, β, γ, etc.) correspond to neural oscillatory activity at the LFP level[57]. These oscillations result from the phase coupling of numerous neurons within specific frequency ranges.

The human neocortex consists of six distinct layers, labeled sequentially from the outermost layer (I) to the innermost (VI). Layers III and V are particularly notable for their high density of pyramidal neurons, which derive their name from the characteristic pyramidal shape of their cell bodies and the orientation of their dendrites[50,58]. A critical feature for EEG signal generation is the alignment of the apical dendrites of pyramidal neurons, which are predominantly oriented perpendicular to the cortical surface, with their cell bodies located in deeper cortical layers. When the apical dendrites undergo depolarization due to excitatory postsynaptic potentials (EPSPs), while the cell body or axonal regions remain near the resting potential or assume an opposite polarity, this differential distribution of charges creates an electrical dipole. This dipole, with its separation of positive and negative charges between the dendritic tips and the soma, is a fundamental source of the cortical electric fields measurable by EEG[56].

In electrophysiology, a "dipole" refers to a pair of spatially separated charges or potentials of equal magnitude but opposite sign. Applied to neurons, the commonly discussed terms "current source" and "current sink" describe the directionality of postsynaptic current flow between the soma and dendrites, which creates a relatively stable potential difference [59]. A current sink refers to the influx of external current into the dendritic region when excitatory inputs depolarize the membrane potential at the dendritic tips. In contrast, the soma or deeper cortical layers exhibit an opposite polarity to the external current, forming a current source. When tens of thousands or more pyramidal neurons exhibit this "source-sink" configuration with aligned or nearly aligned timing, their collective dipole effects are summated, generating detectable potential differences at the scalp surface [60]. Conversely, if the neurons are dispersed in orientation or phase, their dipole effects cancel each other out, significantly reducing the overall strength of the EEG signal.

Under ideal conditions, if the dendrite-soma orientations of all pyramidal neurons were perfectly aligned, synchronized depolarization or hyperpolarization would result in the complete summation of individual dipoles into a large-scale total dipole field. However, in the human brain, cortical architecture is not perfectly uniform and varying excitatory and inhibitory inputs coexist across different regions. Despite these deviations, the relatively consistent alignment of pyramidal neurons within cortical areas is sufficient for the synchronized activity within a specific region at a given time to summate into a macroscopic field potential. This collective activity constitutes a major contributor to the generation of EEG signals[61].

EEG signals are typically divided into several frequency bands, including δ (0.5–4 Hz), θ (4–7 Hz), α (8–13 Hz), β (13–30 Hz), and γ (>30 Hz), each associated with specific functional states of the brain. The appearance of these oscillatory bands in scalp EEG fundamentally arises from the approximate phase or frequency synchronization of large populations of neurons within their respective network couplings[62,63]. When the degree of phase coupling is sufficiently high, reflecting strong large-scale neuronal synchrony, the oscillatory amplitude becomes more pronounced and detectable on the scalp. Conversely, randomization of neuronal phases leads to significant cancellation of signals, resulting in “flat” or low-amplitude EEG patterns[64,65].

In addition to the synchronization of neurons within local cortical regions, the brain exhibits long-range coupling across regions and even hemispheres. This coupling can be mediated by white matter tracts or by thalamic and inter-cortical projections[66,67]. Long-range synchronization contributes to global oscillatory patterns in EEG, such as whole-brain α wave activity or γ waves observed during multisensory integration[57]. Thus, EEG signals reflect not only the summation of local cortical dipoles but also the coordinated activity of multi-level neural networks [68,69].

1.4.2. EEG transmission and recording

From the cortex to the scalp, EEG signals undergo attenuation and dispersion as they pass through multiple layers of biological tissue, a process collectively referred to as volume conduction[70,71]. The media through which the signals propagate include gray matter, white matter, cerebrospinal fluid, the skull, and the scalp. Ultimately, this process results in microvolt-level potential fluctuations on the scalp surface, which are then amplified and recorded by electrodes and amplifiers. From an electrophysical perspective, the dipole fields within the brain can be approximated as point sources or multiple current sources located at various positions. During volume conduction, these currents undergo attenuation and dispersion due to the anisotropic properties of brain tissues and the skull [72,73]. This process generates the potential distribution on the scalp, which typically manifests as regions of positive or negative polarity or as gradual potential gradients [74].

After passing through the skull and scalp, EEG signals form microvolt-level temporal fluctuations on the scalp surface, which require detection, amplification, and digitization using electrodes and amplifiers [75]. Standard electrode placement systems, such as the 10-20 system, utilize scalp locations labeled F, C, P, O, and T. More detailed systems, including the 10-10 and 10-5 systems, allow for high-density EEG recordings with 64, 128, or even 256 channels [76]. Common electrode types include wet electrodes (e.g., Ag/AgCl), dry electrodes, and flexible electrodes[77] [78].EEG measurements also require an online reference electrode. Common referencing methods include monopolar referencing (e.g., Cz, or earlobes A1 and A2), average referencing, and bipolar derivations. The choice of reference affects the polarity and amplitude of recorded waveforms [79,80]. During EEG acquisition, signals must be amplified and filtered. Raw EEG signals, typically only tens of microvolts in amplitude, require amplification and noise reduction to improve signal quality [81,82]. Online acquisition often employs bandpass filtering and notch filtering to remove electromyographic artifacts and line noise. The digitized EEG data are then stored for subsequent analysis.

1.4.3. Advantages of EEG

EEG possesses high temporal resolution, enabling the capture of rapid brain dynamics on a millisecond scale, in contrast to fMRI (in the range of seconds) or PET (in the range of minutes)[83]. Leveraging this temporal precision, researchers can analyze millisecond-level changes in brain electrical activity following external stimuli or internal events, such as the classic ERP components P300 and N400, to investigate the neural mechanisms underlying processes like perception, attention, and memory[84].Additionally, EEG is characterized by its non-invasiveness and safety. Unlike imaging techniques such as X-rays, PET, or CT, EEG does not involve ionizing radiation or contrast agent injections, posing minimal risk to participants [85]. It can be safely applied to special populations, including neonates, pregnant women, and the elderly, making it ideal for longitudinal or repeated-measure studies[86]. EEG also offers advantages in cost and flexibility. The equipment is relatively lightweight, particularly modern wireless EEG systems, allowing applications in hospital rooms, laboratories, and even outdoor or home environments[87,88]. Compared to large-scale instruments like fMRI and MEG, EEG systems are more affordable to acquire and maintain and do not require specialized facilities such as shielded rooms or cooling systems[56].Advances in dry electrode technology and wireless modules (e.g., Bluetooth/Wi-Fi) have further expanded the utility of EEG, enabling continuous monitoring in dynamic or everyday environments [89]. Long-term monitoring generates multi-channel EEG data that facilitates the construction of individualized brain state models, providing novel avenues for precision medicine and adaptive human-machine interaction[90].

1.4.4. Applications of EEG

EEG technology is widely applied in clinical diagnosis and monitoring, neuroscience and cognitive research, brain-computer interfaces (BCIs), and human-computer interaction. Its high sensitivity to epileptic discharges, such as spikes and sharp waves, makes EEG an essential tool for diagnosing epilepsy, determining seizure types, and guiding surgical resection [91,92]. Continuous EEG monitoring can detect subclinical epileptiform discharges, enabling timely adjustments in treatment [93]. Event-related potentials (ERPs) are used to study brain responses to emotional stimuli, such as facial expressions, shedding light on the neural mechanisms underlying socio-emotional cognition [94].By eliciting synchronized oscillations through visual stimuli with different flicker frequencies, EEG can be used to construct high-throughput brain-controlled interfaces for spelling or device selection[95]. Furthermore, EEG can measure user metrics such as attention levels, providing real-time brain state feedback for applications in VR/AR, education, training, and driving safety[96,97].

Overall, EEG excels in temporal resolution, offering an irreplaceable window for millisecond-level tracking of brain processes. Its portability and cost-effectiveness make it broadly applicable in both clinical and research settings. As trends in high-density, wearable, and intelligent EEG systems continue to evolve, technology poised to play an even greater role in diverse scenarios, including healthcare, neurorehabilitation, interactive entertainment, and human-machine collaboration.

1.5. ERP Analysis

Event-Related Potentials (ERPs) are neural electrophysiological signals derived from EEG by time-locking the recorded brain activity to specific external events (e.g., visual or auditory stimuli) or internal events (e.g., cognitive decision-making or motor preparation). These signals are obtained by averaging data across multiple trials to reduce noise and enhance the event-specific response [83].ERPs are characterized by a series of distinctive peaks and troughs in the time domain, such as N1, P2, N2, and P3. These components are often regarded as markers of the brain's processing of specific sensory, cognitive, or motor information and are known for their millisecond-level temporal resolution. ERPs play an indispensable role in cognitive neuroscience and clinical neurodiagnostic, providing insights into the timing and mechanisms of neural processing[84].

In EEG recordings, the electrical activity of cortical neurons is often obscured by various sources of noise and the effects of volume conduction. However, when an external or internal event occurs, a subset of neurons may fire synchronously within a specific time window, generating event-related, time-locked potential changes [98].By repeatedly presenting the same type of event and performing phase-aligned averaging across trials, the time-locked signals can be cumulatively enhanced, while unrelated random brain activity and noise are canceled out. This process results in an ERP waveform with a significantly improved signal-to-noise ratio, facilitating the analysis of event-specific neural dynamics.

ERP typically consists of several peaks or troughs, referred to as "components," which are named based on their polarity (positive/negative) and latency (time of occurrence)[83].Early components (0–100 ms), such as P1 and N1, are generally associated with primary sensory processing. Mid-latency components (100–300 ms), including N2 and P2, are related to processes such as selective attention and stimulus discrimination. Late components (>300 ms), such as P3 (P300), N400, and LPC (Late Positive Component), are more indicative of higher-order cognitive processes, including working memory, semantic processing, and emotional responses [83].

Before calculating ERPs, the EEG data must undergo preprocessing. Common preprocessing steps include filtering, artifact removal, segmentation, and baseline correction. To eliminate DC drifts and high-frequency electromyographic noise, a bandpass filter with an appropriate range (e.g., 0.1–30 Hz or 0.1–40 Hz) is applied based on the study requirements. Independent Component Analysis (ICA) or other techniques are then employed to identify and remove artifacts such as ocular and muscular noise [83].Next, EEG segments are extracted around the events of interest (e.g., stimuli or responses), typically within a time window such as -200 ms to 800 ms. Baseline correction is performed using the pre-event period (e.g., -200 ms to 0 ms) to normalize the data, enabling accurate analysis of component amplitudes and latencies[99].

After preprocessing, the next step is to perform averaging on the data. The classical averaging method involves phase-aligning EEG segments corresponding to the same type of event and averaging them point by point. This approach enhances the signal-to-noise ratio while preserving the event-locked brain activity components [83].For comparative analysis between conditions, segments from different event types can be averaged separately and then subtracted (e.g., deviant stimulus - standard stimulus) to obtain a difference wave. This method highlights specific cognitive processes, such as the Mismatch Negativity (MMN), which reflects the detection of deviations in auditory stimuli [100].

1.6. Time-frequency analysis

Beyond traditional time-domain analysis, such as event-related potentials (ERPs), time-frequency analysis has become a crucial tool in EEG research. EEG signals contain various neural oscillations with distinct frequency characteristics (e.g., δ, θ, α, β, γ), which often exhibit dynamic changes over time during cognitive tasks or pathological states. Simple time-domain averaging can cancel out oscillatory activity with inconsistent phases, whereas time-frequency analysis allows for the simultaneous examination of the power or phase variations of EEG signals across both time and frequency domains. This approach provides a more comprehensive understanding of the role of neural oscillations in processes such as perception, memory, emotion, and language[101,102].

EEG signals can be conceptualized as time series; however, their spectral characteristics often exhibit non-stationarity across different time intervals [103]. Time-frequency analysis aims to decompose the signal on the time-frequency plane, capturing the temporal dynamics of energy or phase changes at different frequencies and linking these changes to cognitive or pathological events [104,105].

This approach is particularly critical for detecting evoked and induced oscillations, rhythm coherence, and cross-electrode synchronization phenomena.

Common techniques for time-frequency transformation include Short-Time Fourier Transform (STFT), Wavelet Transform, and Hilbert Transform. STFT divides EEG data into a series of short time windows, applies Fourier Transform to each window to extract the frequency distribution within that segment, and slides the window across time to generate a time-varying spectrogram [106]. Commonly used window types include Hamming, Hanning, and polynomial windows. The choice of window length determines the trade-off between time and frequency resolution: longer windows improve frequency resolution but reduce temporal precision, whereas shorter windows enhance temporal resolution at the cost of frequency precision[107]. Wavelet Transform employs scalable and translatable wavelet basis functions (e.g., Morlet, Paul, or mother wavelets) to convolve with the signal at multiple scales. This approach provides coefficients that represent the signal's frequency content at different scales and time points [108]. The Morlet wavelet is particularly favored for EEG time-frequency analysis due to its tunable center frequency and bandwidth, making it well-suited for capturing phase and power dynamics of brain oscillations [109].

Time-frequency analysis has become a pivotal tool in EEG research. Compared to traditional time-domain averaging, time-frequency analysis can capture phenomena such as phase inconsistencies or dynamic frequency band shifts, exemplified by the role of induced γ oscillations in perceptual integration [110]. It is also widely used in studies of event-related synchronization/desynchronization (ERS/ERD)[85], offering a richer understanding of neural oscillatory activity than traditional time-domain methods.

1.7. Research goals and content

The primary aim of this study is to elucidate the neural mechanisms underlying auditory-tactile integration by addressing three key questions:

1. Can auditory-tactile integration occur, and is there consistency in auditory-tactile integration between the left and right hemispace?

2. What is the spatiotemporal distribution of auditory-tactile integration? How does attention influence auditory-tactile integration, and is this influence modulated by the spatial location of stimuli?

3. What are the neural oscillatory patterns under multisensory auditory-tactile stimulation? Are these patterns modulated by attention and the spatial location of stimuli?

The main content of each chapter is outlined as follows.

In chapter 1, the concept of multisensory integration, the influence of attention on multisensory processing, the theory of event-related potentials, and the theory of time-frequency analysis were introduced. Also, the purpose and content of this thesis were briefly introduced.

In Chapter 2, the experimental design, experimental setup, parameters of EEG acquisition, and participant information of this study were introduced.

In Chapter 3, we analyzed behavioral data. Auditory-tactile integration was measured from three perspectives: reaction time, accuracy, and race model analysis, when stimuli were presented in the left and right hemispaces, respectively.

In Chapter 4, we performed an event-related potential analysis of the EEG data. The temporal and spatial distribution of auditory-tactile integration was compared under different attention conditions when the stimulus was presented in the left or right hemispace.

In Chapter 5, we investigated the power of each frequency at different time stages for each modality type under different attentional conditions by means of time-frequency analyses and further investigated the interaction between attention and auditory-tactile integration.

In Chapter 6, we summarize the results of behavioral, event-related potential, and time-frequency analyses, draw general conclusions, and propose ideas for future research.

2. Experiment Design

2.1. Participants

Twenty participants (11 males, aged 18–34 years, mean age=24.2 years) were included in this study. All the participants had normal hearing and tactile senses and re-ported having a right-hand preference. No participants reported a history of neurological disorders. Before the experiment started, the experimenter informed the participants of the entire experimental process, task operations and matters needing attention, and conducted a preliminary pre-experiment to determine that the participants could successfully complete the experiment before the formal experiment began. The participants all signed informed consent forms for the experiment and received a certain amount of compensation for their participation. This study was approved by the local ethics committee.

2.2. Stimuli

Tactile (T) and auditory (A) stimuli were presented during the task. The stimuli were divided into standard stimuli and target stimuli. The T stimuli were delivered to the fingertips of the left and right index fingers of the participant via a customized piezoelectric braille display (Piezo stimulator, SC9 device, KGS Co., Japan). As shown in Figure 2.1, the standard T stimuli were the second and third rows of raised probes, and the target stimuli were the first and fourth rows of raised probes. The A stimuli was delivered to the participant's left and right ears through soundproof headphones. The standard stimulus was a pure tone of a 1000 Hz sine wave, and the target stimulus was white noise. The loudness of both the standard stimulus and the target stimulus was 60 dB(a).

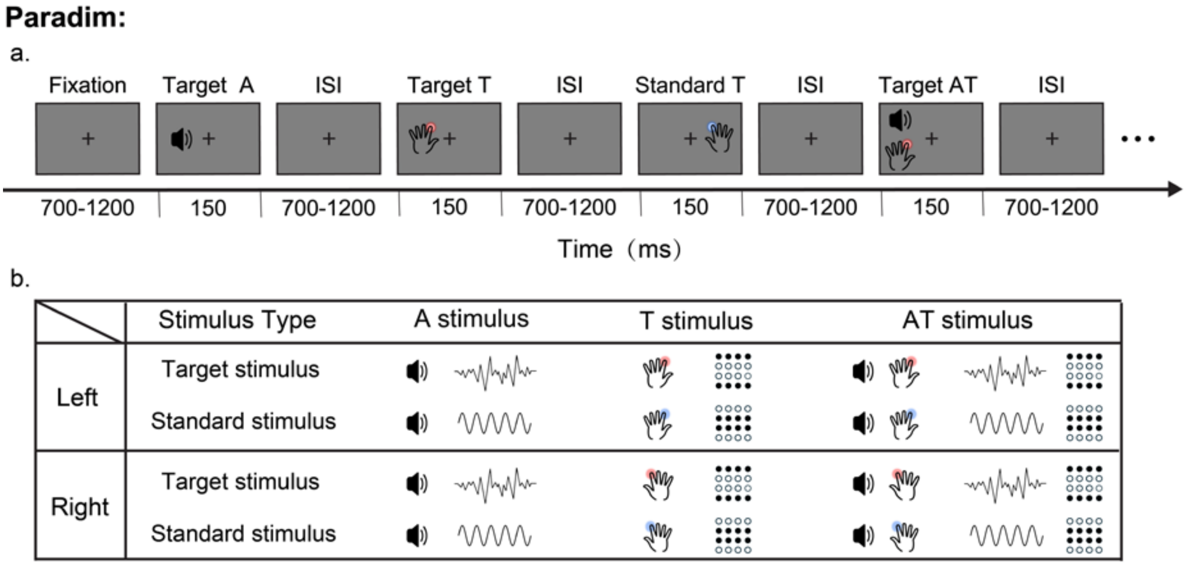

Figure 2.1 Experimental paradigm. (a) Sequence of events and their duration. (b) Stimulus conditions: There were 12 stimulus conditions in total: 8 unisensory stimuli (4 standard stimuli and 4 target stimuli) and 4 multisensory stimuli (2 standard stimuli and 2 target stimuli). The black dots in the tactile stimulus column indicate that the probe was raised.

2.3. Procedure

The experiment was conducted in a dimly lit room with sound attenuation and electrical shielding. Each participant completed 10 blocks, with each block containing 80 A, 80 T, and 80 auditory–tactile (AT) stimuli. The target A, T, and AT stimuli were presented with 20% probability. Each stimulus (2 (standard and target) × 3 (A, V, and AT)) was presented in pseudorandom order with equal probability to the left and right of the participant. The duration of the stimuli was 150 ms, and the interstimulus intervals were randomized between 700 and 1200 ms to avoid anticipation effects.

The participants were seated in a comfortable chair with their head placed in a chin rest for head position fixation. Their hands were naturally placed on the table with the forearms perpendicular to the body plane and 70 cm between the left and right hands. Before the start of each block, the participants were instructed to attend to all the stimuli on one side (left or right). The participants were asked to complete several practice blocks to understand the task. To avoid motion artifacts, the participants were also instructed to minimize blinking and body movements. During the experiment, participants were required to fixate on the centrally presented fixation point and attend to the stimuli on one side while ignoring all the stimuli on the other side. The participants were instructed to press the pedal with their right foot as quickly and accurately as possible when they heard and/or felt the target stimulus. The participants were required to attend to all the stimuli on the left side in five blocks and to attend to all the stimuli on the right side in another five blocks. The two types of blocks alternated. The participants were free to rest between blocks.

2.4. Data acquisition

2.4.1. Behavioral data recording

The experimental program was coded in MATLAB using Psychtoolbox. The stimulus sequence was played while simultaneously recording the subject's responses. There was a unique code for each type of stimulus in the stimulus sequence. The participant's responses were also uniquely coded, with a response error being coded as 0 and a correct response being coded as 1.

At the beginning of each trial, the time when the stimulus was played, and the corresponding stimulus code are recorded. After the participant responded, the response code of the participant is recorded. The response time of the participant is the relative time between the response code and the stimulus code of the trial, in milliseconds. The log information of the experiment was saved in a csv file. The log information included the subject number, name, gender, age, handedness, stimulus type, stimulus onset time, subject response time, and subject response accuracy. There was a separate log file for each block.

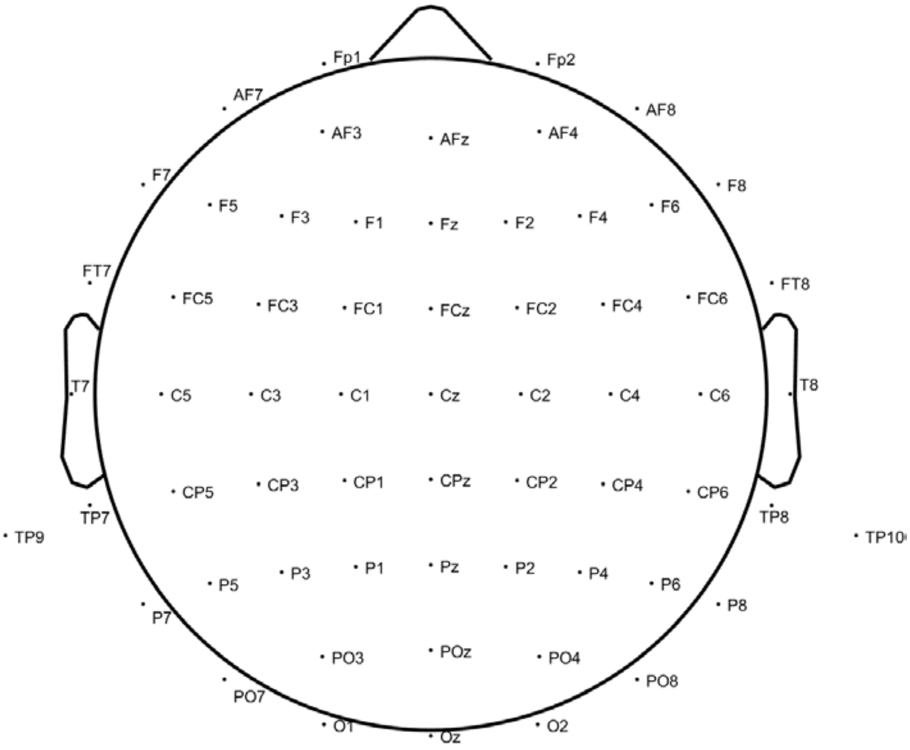

Figure 2.2 Position and mark of electrode placement

2.4.2. EEG signal acquisition

Encephalographic (EEG) data were recorded via a 64-channel EEG cap (Easy-cap, Germany) and a Brain Amp DC amplifier (Glitching, Germany). Horizontal eye movements were recorded from an electrode placed at the outer canthus of the left eye, and vertical eye movements were recorded from an electrode placed below the right eye. The FCz electrode was used as the online reference, with the electrode impedance maintained at 5 kΩ and a sampling rate of 1000 Hz. During the recording process, an online high-pass filter of 0.01 Hz, an online low-pass filter of 100 Hz, and an online notch filter of

60 Hz were set. Recording electrode position according to the international standard 10-20 system, the electrodes were placed as shown in Figure 2.2.

3. Auditory-Tactile Integration Performance Influenced by Spatial Location: A Behavioral Study

3.1. Background

In multisensory integration research, audiovisual integration was the first area to be widely explored, and researchers have gradually expanded to visual-tactile integration, somatosensory-visual integration, auditory-tactile integration, and more complex multisensory integration [111-114]. Compared to audiovisual integration, auditory-tactile integration involves different peripheral sensory pathways. Tactile perception is mainly related to the spatial orientation of body parts and surface perception, while auditory perception is more dependent on the head and ears to encode the spatial orientation or intensity differences of sounds in space[115]. Therefore, auditory-tactile integration has its own characteristics in terms of temporal and spatial features. In recent years, some studies have shown that auditory stimuli can also affect the processing and response of tactile stimuli in tactile spatial orientation tasks[116]. However, there are no systematic and clear research conclusions on whether auditory-tactile multisensory integration can occur in both the left and right hemispaces, or whether there are differences in the integration of the left and right hemispaces.

The processing of auditory stimuli is highly dependent on the language processing functions of the left cerebral hemisphere. Studies have shown that in a dichotic listening task, sounds presented in the right ear are more easily perceived (right ear dominance), which is closely related to the auditory language areas of the left brain (e.g., Wernicke's area)[117]. This lateralization is particularly significant for speech tasks but may be relatively balanced in non-verbal auditory tasks. In spatial tasks, the localization of auditory stimuli is influenced by the division of labor between the left and right hemispheres. The right hemisphere is better at processing auditory signals from the left side of space, especially when there is interference from background noise [118]. Research has found that the right hemisphere's advantage is due to its ability to quickly integrate overall sound characteristics such as frequency and rhythm.

Tactile information is transmitted through the spinal cord and thalamus for processing in the somatosensory cortex of the brain, which is predominantly located in the postcentral gyrus. The difference in the division of labor between the left and right hemispheres in tactile processing reflects the lateralized nature of the cerebral cortex. The right hemisphere is primarily responsible for spatial attention and holistic perception. Studies have shown that the right brain's parietal association area and primary somatosensory cortex are more sensitive to tactile inputs from left-sided space[119]. The left hemisphere tends to process the sequential and logical aspects of tactile tasks, such as the semantic categorization or operational analysis of tactile input [120]. This functional difference may cause the brain to process stimuli presented in the left and right hemispaces differently for the same task demands.

Current research on auditory-tactile integration tended not to distinguish between left and right hemispaces or to focus on a single side, e.g., focusing only on the left hemispace or the right hemispace. However, there are differences in spatial perception and control between the right and left sides of the human body. Many researchers suggest that the left hemisphere is more sensitive to analytical processing, language functions, etc., while the right hemisphere is more important in spatial localization and attentional switching [121]. This functional asymmetry might lead to different auditory-tactile integration on different hemispaces. Therefore, whether the same degree of auditory-tactile integration can be achieved in both the left and right hemispaces, or whether there are lateralized differences in the integration time window and intensity, would need to be further investigated.

To answer the questions above, we investigated the participants' multisensory integration performance using behavioral data. The differences in multisensory integration when stimuli were presented in the left or right hemispace were analyzed and compared by response time, accuracy, and race model.

3.2. Response time

The data was filtered to exclude behavioral data with incorrect responses, and subsequent reaction time data analysis was based on correct responses. RT was defined as the time from stimulus onset to the end of the participant pressed the button.

Table 3.1 Response time (standard deviation, ms)

	Left	Right
A	566.31(48.76)	554.83(62.08)
T	607.23(49.68)	621.09(68.56)
AT	503.78(57.97)	505.53(69.22)

As shown in Figure 3.1, a repeated measures analysis of variance was performed on reaction times 2 (spatial location: left, right) × 3 (stimulus type: auditory stimulus, tactile stimulus, auditory-tactile stimulus). The results showed that the main effect of stimulus type was significant, $F(1.565, 29.738) = 71.504$, $p < 0.001$, $\eta p^2 = 0.790$, that is, there were significant differences in reaction times between different stimulus types. The interaction between stimulus type and spatial location was significant, $F(1.910, 36.286) = 5.129$, $p = 0.012$, $\eta p^2 = 0.213$.

Simple effect analysis found that when the stimulus was presented in the left hemispace, there was a significant difference between the response time to the auditory-tactile stimulus and to the auditory stimulus, $t(19) = -6.904$, $p < 0.001$, *Cohen's d*=-1.395, the reaction time to the auditory-tactile stimulus (503.78) was significantly faster than the reaction time to the auditory stimulus (566.31). There was also a significant difference between the response times to auditory-tactile stimuli and to tactile stimuli, $t(19)=-15.967$, $p<0.001$, *Cohen's d*=-2.307, with the response time to the auditory-tactile stimuli (503.78) significantly faster than that to the tactile stimuli (607.23).

When the stimulus was presented in the right hemispace, there was a significant difference between the response times to the auditory-tactile and auditory stimuli, $t(19)=-6.664$, $p<0.001$, *Cohen's d*=-1.099, the response time to the auditory-tactile stimulus (505.53) was significantly faster than the response time to the auditory stimulus (554.83). There was also a significant difference between the response times to auditory-tactile stimuli and tactile stimuli: $t(19)=-10.298$, $p<0.001$, *Cohen's d*=-2.577, the response time to the auditory-tactile stimuli (505.53) was significantly faster than to the tactile stimuli (621.09).

Therefore, there is a significant advantage in bimodal processing of auditory-tactile stimuli, regardless of whether the stimuli are presented in the left hemispace or the right hemispace.

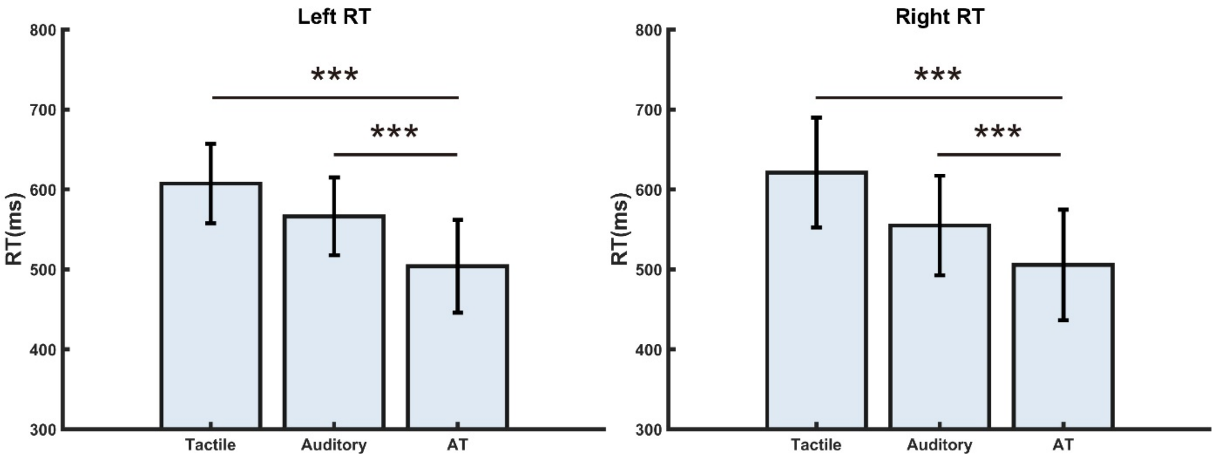

Figure3.1 Statistical difference of response time between groups

3.3. Response accuracy

The correct rate of the participants' answers was analyzed. The correct rate was defined as the percentage of the total number of stimuli answered correctly by the participants. The correct rates of the answers under the six experimental conditions are shown in the table below.

Table 3.2 Response accuracy (standard deviation)

	Left	Right
A	0.931(0.078)	0.970(0.033)
T	0.890(0.091)	0.877(0.084)
AT	0.975(0.032)	0.985(0.022)

As shown in Figure 3.2, a repeated measures analysis of variance was performed on the accuracy rate with 2 (spatial location: left and right) × 3 (stimulus type: auditory stimulus, tactile stimulus, and auditory-tactile stimulus) factors. The results showed that the main effect of stimulus type was significant, $F(1.369, 26.020) = 17.010$, $p < 0.001$, $\eta p^2 = 0.472$, and there were significant differences in accuracy rates between different stimulus types.

There was no significant interaction between spatial location and stimulus type. One-way repeated measures ANOVA was performed separately for stimuli presented in the left hemispace and the right hemispace. When the stimuli were presented in the left hemispace, there was a significant difference between the accuracy rates of the haptic and auditory stimuli, *t*(19)=4.677, *p*<0.001, *Cohen's d*=1.066, the accuracy rate of the haptic stimuli (0.975) was significantly higher than that of the auditory stimuli (0.890). When the stimuli were presented in the right hemispace, there was a significant difference between the accuracy rates of the auditory-tactile stimuli and the tactile stimuli, *t*(19)=5.278, *p*<0.001, *Cohen's d*=1.273, and the accuracy rate of the auditory-tactile stimuli (0.985) was significantly higher than that of the tactile stimuli (0.877).

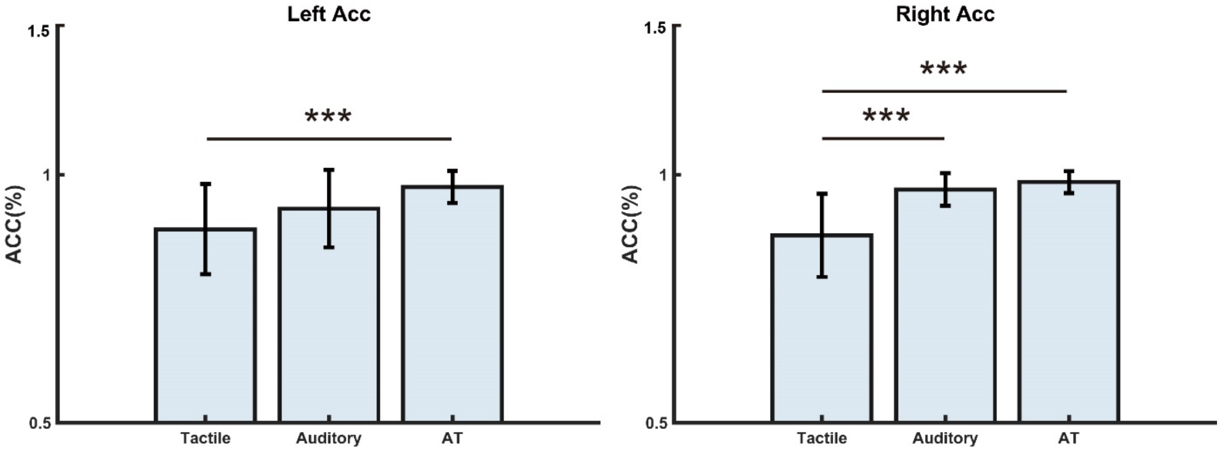

Fig3.2 Statistical difference of response time between groups

3.4. Race model

The race model was proposed by Miller (1982), and its formula is shown in Equation 3-1:

$$P(RT < t|S_1 \; and \; S_2) \leq P(RT < t|S_1) + P(RT < t|S_2) - P(RT < t|S_1) \times P(RT < t|S_2)$$

where S1 and S2 represent two different sensory modalities, such as auditory and tactile, and P is the cumulative probability distribution function, which represents the probability of responding at any given time t. The meaning of this inequality is that if the processing of bimodal information conforms to the competition model, then the participant's response to the bimodal stimulus cannot be faster than the fastest of the two responses to the single-modal stimuli. That is, within a given time period, the probability of responding to the bimodal stimulus is less than or equal to the sum of the probabilities of responding to the two single-modal stimuli. And when this inequality does not hold, the co-activation model is accepted, which means that multisensory integration has occurred.

The probability values under different stimulus types were calculated at intervals of 1 ms within the response time range of 0–1000 ms. The cumulative distribution probabilities of the binaural auditory-tactile stimuli and the cumulative distribution probabilities of the competitive model are shown in Figure 3.3. The difference between the two was subjected to a paired t-test. The results show that when the stimulus is presented in the left hemispace, the time window for multisensory integration is 368–594 ms, and when the stimulus is presented in the right hemispace, the time window for multisensory integration is 407–583 ms. Furthermore, the difference in CDF when the stimulus is presented in the left hemispace is greater than the difference in CDF when the stimulus is presented in the right hemispace. The above results show that when the stimulus is presented in the left hemispace, the effect of auditory-tactile integration is stronger.

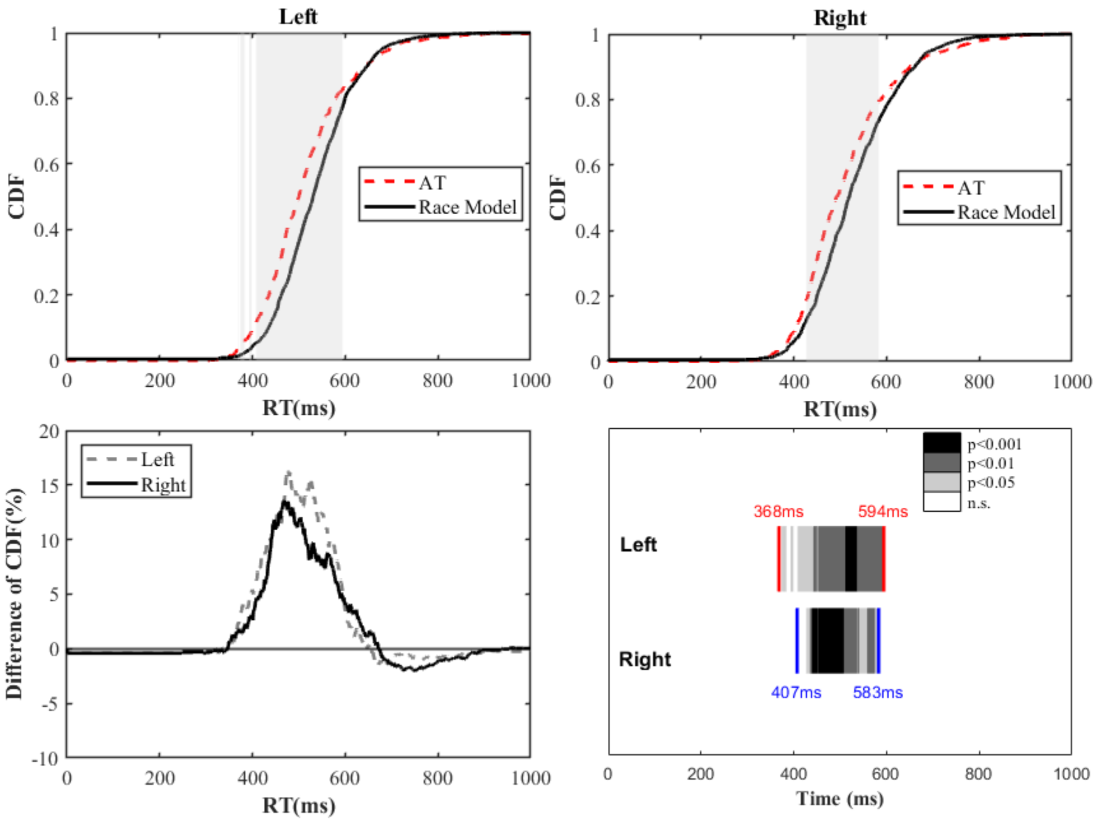

Fig3.3 Race model analysis

3.5. Discussion

The purpose of this experiment was to investigate whether auditory-tactile integration can occur when the stimulus is presented in the left hemispace and the right hemispace, and whether there is a difference in auditory-tactile integration under these two conditions.

By analyzing the participants' responses, it was found that whether the stimulus was presented on the left or right, the participants' response time to binaural auditory-tactile stimuli was significantly faster than that to monaural auditory or tactile stimuli. A significant bimodal processing advantage was found, which demonstrated that auditory-tactile integration could occur regardless of whether the stimulus was presented in the left or right hemispace.

In addition, the analysis of accuracy also showed a similar trend. Regardless of whether the stimulus was presented in the left or right hemispace, the participants' accuracy in responding to bimodal stimuli was faster than that in responding to either the auditory or tactile unimodal stimuli.

The competitive model analysis found that there was a significant multisensory integration effect regardless of whether the stimulus was presented in the left hemispace or the right hemispace. The cumulative probability distribution of the participants' responses to bimodal auditory-tactile stimuli violated the competitive model. Interestingly, when the stimulus was presented in the left hemispace, the effect of this violation was greater, and the time window for multisensory integration was longer.

3.6. Conclusion

By analyzing the participants' responses, accuracy rates and race models, we found that auditory-tactile integration can occur whether the stimulus is presented in the left hemispace or the right hemispace. Moreover, the multisensory integration effect is stronger when the stimulus is presented in the left hemispace.

4. The Impact of Selective Spatial Attention on Auditory–Tactile Integration: An Event-Related Potential Study

4.1. Background

Attention is a critical cognitive function that regulates sensory information processing, and attention has a significant effect on the efficiency and effectiveness of multisensory integration[18,122]. Attention can increase the processing of relevant sensory information, inhibit irrelevant inputs, and increase perceptual accuracy and response speed[37,123,124]. The temporal dynamics and neural mechanisms of attention in multisensory integration have been further explored in recent studies. For example, Ferrari and Noppeney [125] reported that attention can increase multisensory integration at early sensory processing stages. Elshout et al. [126] investigated the synergistic effect of motion coherence and multisensory integration and reported that visual–auditory integration can significantly increase information processing in the premotor-related visual task stage, indicating that attention has a beneficial effect on the process of multisensory integration. In addition, other studies have shown that multisensory integration may occur automatically in some cases and is not entirely controlled by attention [127]. This automatic integration process may be more obvious when the stimulus intensity is high, the task load is low, or the stimuli are highly consistent in time and space[128,129]. At present, most research has focused on the effect of attention on audiovisual integration, and it is still unclear how auditory–tactile integration is regulated by attention.

The temporal dynamics of multisensory integration involve different neural processing stages that may occur in the ipsilateral and contralateral hemispheres of the brain [129,130]. The early stages of integration usually take place in the primary sensory cortex and are more strongly associated with the hemisphere corresponding to the side on which the stimulus is presented [6]. For example, Foxe et al. [131] reported that the early components of audiovisual integration occur mainly in the hemisphere corresponding to the side on which the stimulus is presented. The later stages of integration involve more cognitive regions, possibly extending across both hemispheres[132,133]. Molholm et al. [134] reported that the later stages of audiovisual integration were significantly represented in both hemispheres, suggesting that multisensory information is integrated across a wide range of brain regions during the cognitive processing stage. For auditory–tactile integration, Murray et al.[135] found through event-related potential (ERP) research that the early component (approximately 50 ms) of auditory–tactile integration mainly occurs in the hemisphere corresponding to the side on which the stimulus is presented, reflecting the rapid response of primary sensory areas to multisensory information. Gobbelé et al. [136] reported that between 75–85 ms and 105–130 ms, somatosensory stimulation is located in the posterior parietal cortex and between the secondary somatosensory cortex and auditory cortex, respectively. Brett-Green et al. [137]reported that, in an ERP study, significant multisensory integration occurred between 60 and 80 ms in the hemisphere opposite that of the somatosensory stimulation and between 110 and 150 ms in the hemisphere ipsilateral to the somatosensory stimulation. Between 180 and 220 ms, significant multisensory integration occurred in both hemispheres. This finding suggests that the integration process may involve complex neural networks and spatiotemporal characteristics, and whether this process can be regulated by attention and how it is regulated by attention remain unclear. Therefore, further research on the hemispheric involvement of auditory–tactile integration at different temporal stages under different attention conditions is required.

The main purpose of this study was to explore the temporal and spatial differences in auditory–tactile integration under different attention conditions and how auditory–tactile integration occurs in the ipsilateral and contralateral hemispheres at different stages of time under the effect of attention. The effect of attention on the neural mechanisms of auditory–tactile integration was revealed by applying ERP analysis on the EEG data within four time windows (70–90 ms, 90–110 ms, 110–130 ms, and 180–220 ms) and seven electrodes of interest (central-parietal: AFz, FCz, and CPz; lateral: C3, C4, CP5, and CP6).

4.2. Data preprocessing

EEG data were preprocessed in MATLAB R2021b via EEGLAB (version 2024.0), and offline analysis was used to re-reference all electrodes to the average value of the bilateral mastoid. The EEG data were bandpass filtered in the range of 0.01–30 Hz, and then the continuous EEG data were segmented (-100~500 ms). Independent component analysis was then performed to remove noise interference, such as that from eye and muscle movements. Artifacts were further corrected by suppressing signals exceeding ±80 μV.

4.3. Data analysis

The effect of multisensory integration was assessed by comparing the responses to multisensory stimuli with the algebraic sum of the responses to unisensory stimuli. If there was a significant difference between the sum of the ERPs to unisensory stimuli and the ERP to multisensory stimuli, then multisensory interaction was said to have occurred[138,139].

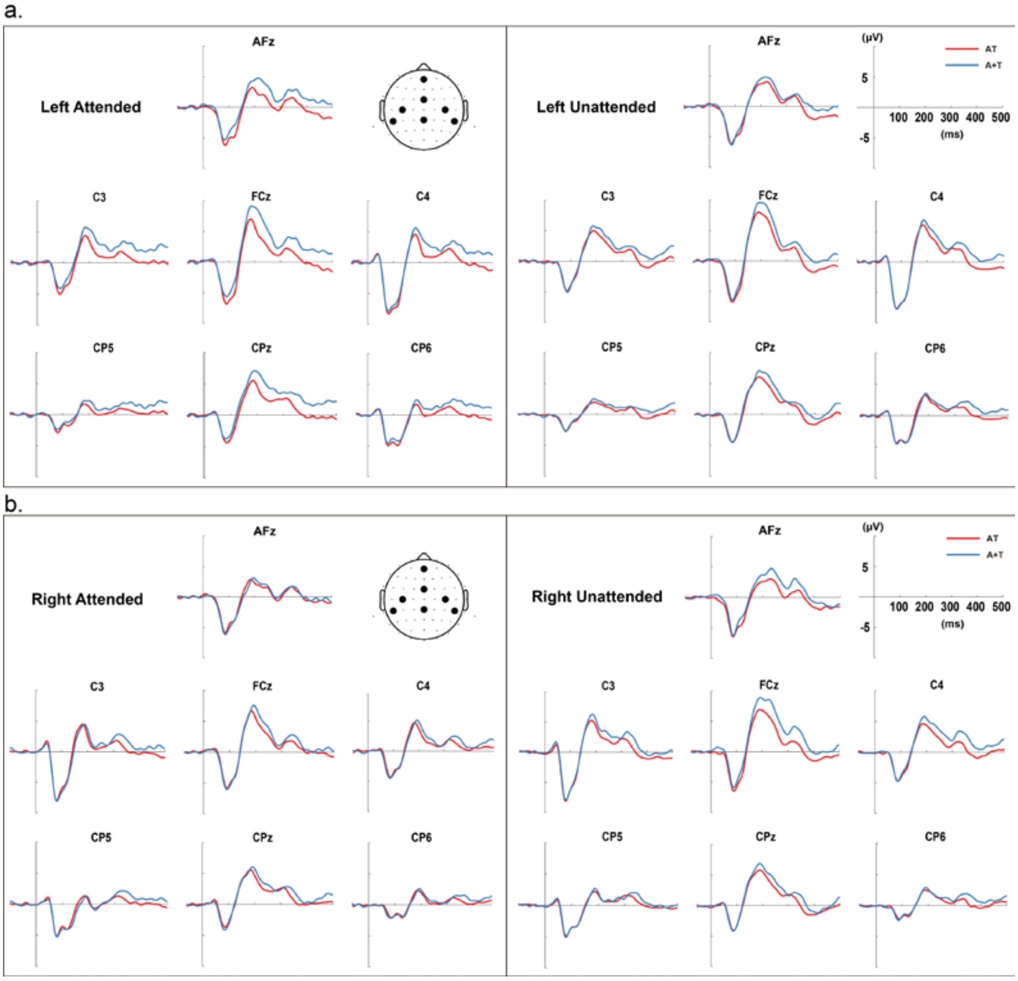

Figure 4.1. Event-related potentials (ERPs). The figure shows the grand average of ERPs for unisensory stimulus summation (blue trace) and simultaneous auditory and somatosensory stimulation (red trace) in 20 participants. ERPs are shown at central electrode positions (AFz, FCz, and CPz) and lateral electrode positions (C3, CP5, C4, and CP6). (a) Stimulus presented in the left hemispace; (b) stimulus presented in the right hemispace.

For ERP analysis, as shown in Figures 4.1 and 4.2, the average amplitude of the neural response to the standard stimulus was calculated for each stimulus condition within selected time windows. On the basis of previous studies and our results, we selected four time windows (70~90 ms, 90~110 ms, 110~130 ms, and 180~220 ms) and seven electrodes (AFz, FCz, CPz, C3, CP5, C4, and CP6) for further analysis.

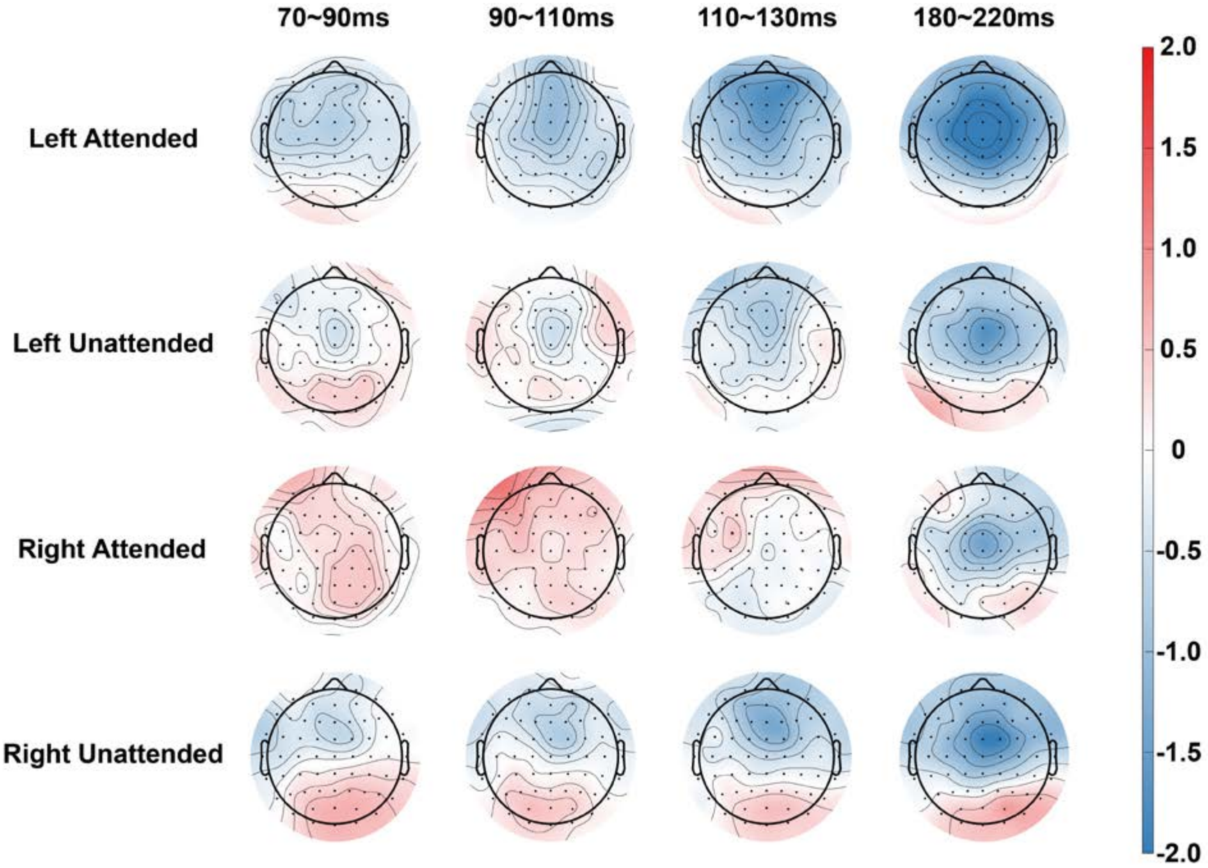

Figure 4.2. Influence of attention on topographic voltage distribution. The topographic voltage distributions of the grand average event-related potential (ERP) components for the standard stimulus in the 4 time windows of interest for attended and unattended stimuli when the stimuli were presented in the left and right hemispaces, respectively. The maps show the mean voltage of AT- (A+T) within the corresponding time windows (70–90 ms, 90–110 ms, 110–130 ms, and 180–220 ms). A, auditory; T, tactile; AT, auditory–tactile.

To examine multisensory integration, a three-way repeated-measures analysis of variance

(ANOVA) was first performed for the central electrodes, separately for stimuli presented on the left and right sides, with the following factors: attention (attended vs. unattended), stimulus type (AT vs. A+T), and electrode position (AFz, FCz, and CPz). For left and right hemispace stimulation at the two pairs of lateral electrodes, the factors in the repeated-measures ANOVA included attention (attended vs. unattended), stimulus type (AT vs. A+T), and hemisphere (same side as the stimuli vs. opposite side of the stimuli). We report only statistically significant effects that included the channel type factor.

4.4. Result

4.4.1. N80(70~90 ms)

When stimuli were presented in the left hemispace, an ANOVA for the central electrode showed a significant main effect of stimulus type [$F(1,19)= 4.493$, $p=.047$, $\eta^2p=0.191$], and subsequent comparisons (paired t-tests) found that there was a significant difference of stimulus type on the 2 electrodes under attended conditions (AFz [$t(19)=2.964$, $p=0.008$, *Cohen's* d=0.313], FCz [$t(19)=2.460$, $p=0.024$, *Cohen's d*=0.395]), and no significant difference of stimulus type was found in the unattended condition. For the lateral electrodes, ANOVA revealed no significant main effects or interactions for stimulus type, and subsequent comparisons revealed a significant difference of stimulus type in the ipsilateral hemisphere in the attended condition (C3 [$t(19)=2.628$, $p=0.017$, *Cohen's d*=0.454]). No significant difference of stimulus type was found in the unattended condition.

For stimuli in the right hemispace, the ANOVA for central electrodes revealed a significant interaction between attention and stimulus type [$F(1,19)= 4.418$, $p=0.049$, $\eta^2p=0.189$] and a significant interaction between stimulus type and electrode position [$F(1,19)= 4.939$, $p=0.021$, $\eta^2 p=0.206$], but subsequent comparisons did not reveal any significant differences related to stimulus type. ANOVA and subsequent comparisons for lateral electrodes did not reveal significant differences in stimulus type. No significant differences in stimulus type were found via ANOVA or subsequent comparisons for the lateral electrodes.

4.4.2. P100(90~110 ms)

For stimuli in the left hemispace, an ANOVA on the central electrode revealed a significant main effect of stimulus type [$F(1,19)= 5.293$, $p=.033$, $\eta^2 p=0.218$] and a significant interaction between stimulus type and attention [$F(1,19)= 5.033$, $p=.037$, $\eta^2 p=0.209$]. Subsequent comparisons revealed significant differences of stimulus type at 3 electrodes in the attended condition (AFz [$t(19)= 4.492$, $p<0.001$, *Cohen's d*=0.469], FCz [$t(19)= 4.580$, $p<0.001$, *Cohen's d*=0.504] and CPz [$t(19)=2.482$, $p=0.025$, *Cohen's d*=0.333]). No significant difference of stimulus type was found in the non-attended condition. For the lateral electrodes, ANOVAs found significant interactions between attention and stimulus type [$F(1,19)= 5.917$, $p=0.025$, $\eta^2 p=0.237$] on the C3/4 electrode pair, as well as significant interactions between attention and stimulus type [$F(1,19)= 4.811$, $p=0.041$, $\eta^2 p=0.202$] on the CP5/6 electrode pair. Subsequent comparisons revealed that significant differences of stimulus type were found in both hemispheres in the attended condition (C3 [$t(19)= 3.312$, $p=0.004$, *Cohen's d*=0.414], CP6 [$t(19)= 2.571$, $p=0.019$, *Cohen's d*= 0.449]). No significant differences in channel type were found in the unattended condition.

For stimuli in the right hemispace, neither ANOVA nor subsequent comparisons of central and lateral electrodes revealed significant differences of stimulus type between attended and unattended conditions.

4.4.3. N100(110~130 ms)

When stimuli were presented in the left hemispace, the ANOVA for the central electrode showed a significant main effect of stimulus type [$F(1,19)= 12.122$, $p=0.002$, $\eta^2p=0.390$] and a significant interaction between attention and stimulus type [$F(1,19)= 5.297$, $p=0.033$, $\eta^2p=0.217$]. Subsequent comparisons revealed significant differences of stimulus type for the 3 electrodes in the attended condition (AFz [$t(19)=5.486$, $p<0.001$, *Cohen's* $d=0.673$], FCz [$t(19)=4.631$, $p<0.001$, *Cohen's* $d=0.660$] and CPz [$t(19)=2.753$, $p=0.013$, *Cohen's* $d=0.448$]). For the lateral electrodes, ANOVA revealed a significant interaction between stimulus type and electrode position [$F(1,19)= 4.850$, $p=0.040$, $\eta^2p=0.203$] on the C3/4 electrode pairs, and no main effect or interaction of stimulus type was found on the CP5/6 electrode pairs. Subsequent comparisons revealed significant differences of stimulus type in the ipsilateral hemisphere for the attended condition (C3 [$t(19)= 3.614$, $p=0.002$, *Cohen's* $d=0.491$] and CP5 [$t(19)= 2.456$, $p=0.024$, *Cohen's* $d=0.283$]) .

When stimuli were presented in the right hemispace, ANOVA for central electrodes revealed a significant interaction between attention and stimulus type and electrode position [$F(1.578,29.983)= 4.625$, $p=0.025$, $\eta^2p=0.196$]. Simple effects analyses revealed a significant difference of stimulus type on the 2 electrodes in unattended condition (AFz [$t(19)=2.714$, $p=0.014$, *Cohen's* $d=0.438$] and FCz

[$t(19)=2.379$, $p=0.028$, *Cohen's* d= 0.475]). Neither ANOVA nor subsequent comparisons for lateral electrodes revealed significant differences of stimulus type in any condition.

4.4.4. P200(180~220 ms)

When stimuli were presented in the left hemispace, an ANOVA for the central electrode showed a significant main effect of stimulus type [$F(1,19)$= 24.342, $p<0.001$, η^2p=0. 562], a significant interaction between stimulus type and attention [$F(1,19)$= 5.942, $p=0.025$, η^2p=0. 238], and a significant interaction between stimulus type and electrode position [$F(1.906,36.212)$= 9.627, $p<0.001$, η^2p=0. 336]. Subsequent comparisons revealed significant differences of stimulus type at 3 electrodes in the attended condition (AFz [$t(19)=3.578$, $p=0.002$, *Cohen's* $d=0.532$], FCz [$t(19)=5.850$, $p<0.001$, *Cohen's* $d=0.912$] and CPz [$t(19)=6.004$, $p<0.001$, *Cohen's* $d=0.666$]), and a significant difference of stimulus type at the 2 electrodes in the unattended condition (FCz [$t(19)=2.989$, $p=0.008$, *Cohen's* $d=0.514$] and CPz [$t(19)=2.817$, $p=0.011$, *Cohen's* $d=0.342$]). For the lateral electrodes, the ANOVA showed a significant main effect of stimulus type [$F(1,19)=19.368$, $p<0.001$, η^2p=0. 505] and a significant interaction between stimulus type and attention [$F(1,19)=4.741$, $p=0.042$, η^2p=0. 200] on the C3/4 electrode pairs. The main effect of stimulus type [$F(1,19)=12.037$, $p=0.003$, η^2p=0. 338] was significant on the CP5/6 electrode pair. Subsequent comparisons revealed significant differences of stimulus type in both hemispheres in the attended condition (C3 [$t(19)$= 5.981, $p<0.001$, *Cohen's* $d=0.819$], C4 [$t(19)=4.170$, $p<0.001$, *Cohen's* $d=0.736$], and CP5 [$t(19)$= 4.483,$p<0.001$, *Cohen's* $d=0.495$] and CP6 [$t(19)$= 2.908, $p=0.009$, *Cohen's* $d=0.499$]), significant differences of stimulus type were also found in the both hemispheres under unattended condition (C3 [$t(19)$= 2.427, $p=0.025$, *Cohen's* d=0.387], C4 [$t(19)$= 2.305, p=0.033, *Cohen's* d=0.429]).

When stimuli were presented in the right hemispace, ANOVA results for the central electrode showed a significant main effect of stimulus type [$F(1,19)$= 8.922, p=0.008, η^2p=0. 0.320], and a significant interaction between stimulus type and electrode location [$F(1,19)$= 9.432, p<0.001, η^2p=0. 332]. Subsequent comparisons revealed significant differences of stimulus type at 2 electrodes in the attended condition (FCz [$t(19)$= 3.281, p=0.004, *Cohen's* d=0.471] and CPz [$t(19)$= 2.795, p=0.012, *Cohen's* d=0.278]) . Significant difference of stimulus type at the 2 electrodes in the unattended condition (AFz [$t(19)$= 2.223, p=0.039, *Cohen's* d=0.374] and FCz [$t(19)$= 3.013, p=0.007, *Cohen's* d=0.691]). ANOVA of the lateral electrodes revealed a significant main effect of stimulus type [$F(1,19)$= 9.844, p=0.005, $\eta 2p$=0. 341] on the C3/4 electrode pair. Subsequent comparisons revealed significant differences of stimulus type in the ipsilateral hemisphere in the attended condition (C4 [$t(19)$= 2.439, p=0.025, *Cohen's* d=0.386]), and in the bilateral hemisphere in the unattended condition (C3 [$t(19)$= 2.723, p=0.013, *Cohen 's* d=0.470], C4 [$t(19)$= 2.538, p=0.020, *Cohen's* d=0.511]).

4.5. Discussion

In this study, ERP technology was used to explore the effect of spatially selective attention on auditory–tactile integration. The ERP experimental results showed that for stimuli presented in the left hemispace, auditory–tactile integration occurred earlier and had a wider spatial range in the attended condition. For stimuli presented in the right hemispace, integration occurred later, and integration occurred in a wider temporal and spatial range in the unattended condition. In addition, the difference in integration between the attended and unattended conditions was not as obvious as when the stimuli were presented on the left side.

When stimuli were presented in the left hemispace, the results showed that there were more brain regions where auditory–tactile integration occurred under the attended condition, and the integration effect appeared earlier. Specifically, in the attended condition, integration was observed at central electrodes AFz and FCz within an early time window of N80 ms, and the extent of integration gradually expanded over time in the subsequent time windows. This finding is consistent with previous studies and indicates that attention can promote multisensory integration the collaborative processing of related sensory information [18,37]. The early integration effect suggests that attention contributes to multisensory integration at the primary sensory processing stage [140]. For example, Talma et al. found that spatial selective attention affects the early P100 component, the integration effect is greater under attended conditions. P100 associates with early sensory processing and primary attention allocation, affecting primary sensory filtering and perceptual enhancement [141,142]. N100 (or N1) generally considered a indicator of selective attention at the perceptual stage, associated with enhanced discrimination and orientation to the features and location of stimuli [143]. P200 (or P2) generally relates to mid- or late-stage cognitive processing, including stimulus categorization, semantic integration, and higher-level perceptual decision-making[144]. This phenomenon may be due to the fact that attention increases the excitability of the sensory cortex and increases sensitivity to multisensory stimuli [122]. In addition, frontal regions are involved in attentional control and higher cognitive functions[145], and the activation of frontal regions suggests that attention may regulate the early processing of auditory–tactile integration through frontal regions[15]. For the lateral electrode analysis, significant integration was found at N80 ms and N100 ms on the side of the brain ipsilateral of the stimulus and at P200 ms on both sides of the brain; these findings are consistent with previous research results [136,137]. In the time window of P100 ms, previous studies have revealed multisensory integration only in the ipsilateral hemisphere[146]. Our results revealed significant integration in the contralateral hemisphere, which may be due to the addition of attentional resources.

Conversely, when the stimuli were presented in the right hemispace, more brain regions were involved in auditory–tactile integration in the unattended condition, and the integration effect mainly appeared in a later time window (N100 and P200). This finding indicates that for stimuli in the right half of space, auditory–tactile integration may be more dependent on automated processing and relatively less affected by attention. This indication is consistent with the view expressed in some studies that multisensory integration may occur automatically in some cases [129,147]. The results of the analysis of the lateral electrodes also revealed the same trend, with later integration shown at the lateral electrodes, which occurred only within a time window of P200. Under the attended condition, integration occurred significantly earlier in the ipsilateral hemisphere than in the contralateral hemisphere, whereas under the unattended condition, integration occurred in both hemispheres. These results suggest that for stimuli in the right hemispace, auditory–tactile integration requires a longer processing time and that the influence of attention is more limited.

Our results showed that spatial location has a significant effect on the temporal dynamics of auditory–tactile integration and the pattern of brain region activation. Attention facilitated auditory–tactile integration when the stimuli was presented in the left hemispace. This finding may be related to the advantage of the right hemisphere in processing stimuli in the left hemispace and spatial attention tasks. The right hemisphere is widely considered to have greater processing capacity for spatial attention and multisensory integration, especially for stimuli in the left hemispace [148,149]. This hemispheric dominance means that when stimuli appear in the left half of space, the right hemisphere can more effectively regulate and integrate information from different sensory modalities, thus achieving a wider integration effect in an earlier time window. In addition, the right hemisphere not only dominates spatial attention, but is also more strongly connected to the integration network of multiple sensory channels [132,150,151]. This highly efficient functional connectivity allows the right hemisphere to quickly and extensively activate relevant brain regions in response to auditory–tactile stimuli in the left half of space, promoting integration effects over a wider range and over a longer period.

4.6. Conclusions

This study revealed that spatially selective attention and the spatial location of stimuli significantly affect the temporal dynamics of auditory–tactile integration and the pattern of brain region activation. Specifically, in the left half of the space, auditory–tactile integration occurred earlier and involved a wider range of brain regions under the attended condition, whereas in the right half of the space, auditory–tactile integration occurred earlier and involved a wider range of brain regions under the unattended condition. In addition, auditory–tactile integration involved the ipsilateral and contralateral hemispheres at different stages of time, reflecting the complexity and dynamics of multisensory integration. These findings provide new perspectives for understanding the neural mechanisms of multisensory integration and are highly important for theoretical research and practical applications in related fields.

5. Attention Affects Auditory-Tactile Integration: Evidence From Event-Related Oscillations

5.1. background

Event-Related Oscillations (ERO) refer to the phenomenon of systematic changes in the time or phase of brain oscillatory activity after the occurrence of a specific stimulus or event. This can be expressed as an increase in amplitude, phase reset, or a change in the level of synchronization. Compared to the traditional event-related potential (ERP), EROs emphasize the rhythmic changes in one or more frequency bands of the brain electrical signal and can distinguish between “phase-locked” and “non-phase-locked” components.

Gamma oscillations typically refer to high-frequency oscillations of between 30 and 100 Hz. Gamma oscillations are closely related to a variety of high-level cognitive functions, including but not limited to: attention focusing, working memory maintenance, perceptual feature binding, multisensory integration, language processing, episodic memory, and executive control. Recently, researchers have also gradually come to consider abnormal patterns of gamma oscillations as important biomarkers for certain neurological or psychiatric disorders.

Multisensory integration usually involves different primary sensory cortices (such as V1, A1, S1, etc.) and cross-modal association areas (such as the temporo-parietal junction, superior temporal sulcus, insula, etc.). Studies have found that when multisensory stimuli are presented simultaneously and require integration, these brain regions show an increase in coherence in the gamma band[152]. This phase synchronization in the high-frequency band was found to be a critical link for the brain to achieve "binding" of information from multiple sources. Event-related gamma power or phase changes can be detected in EEG/MEG recordings when multisensory stimuli are temporally synchronized or strongly correlated. This synchronization enhancement, compared to single-channel stimulation, indicates an efficient coupling and integration process of brain features across modalities[153]. High-frequency gamma oscillations typically originated from rhythmic discharges in local neural networks centered on inhibitory interneurons such as PV+ basket cells. These fast firings help to "align" dispersed neural activities within a time window of milliseconds when multisensory information arrives at the relevant cortex, thus forming a cross-sensory synchronous processing.

Research found that when an individual oriented their attention to a sensory modality (e.g. visual, auditory) or a spatial location, the gamma power in the corresponding cortical area was significantly increased, which was consistent with a more sensitive perceptual threshold or faster reaction speed [154]. At the same time, the processing of non-target or distracting information was inhibited or synchronously decreased in the gamma band. Through rapid phase locking of inhibitory neurons in local circuits, the brain can "block out" distractions in a very short period, allowing task-relevant information to pass through preferentially. When attention was sustained or under high load, researchers observed that the phase of α/β could modulate the amplitude of γ, forming phase-amplitude coupling (PAC), which reflects the synergy of multi-level oscillations [155]. The prefrontal and parietal lobes fine-tune the local excitatory-inhibitory balance in the sensory cortical target through neurotransmitters (e.g., norepinephrine) and neural regulatory loops, thereby affecting the bandwidth and synchronization strength of γ [156].

A significant temporal and feature match between different modalities of stimulation can more strongly stimulate the brain's gamma band resonance, thereby attracting or strengthening attention. Behaviorally, this is manifested in faster detection and lower error rates. If the experimental task instructions require attention to be focused on only one of the sensory modality or certain features, attention will enhance the gamma activity of the brain regions related to it, while suppressing the high-frequency response of other modalities, reducing interference or resource dispersion.

Gamma oscillations play an indispensable role as a “high-frequency synchronizer” in two important cognitive functions: multisensory integration and attention. From the perspective of multisensory integration, gamma waves make it possible for dispersed brain areas to “bind” information on an extremely short timescale. From the perspective of attention, gamma waves give stronger selective gains to target modalities and suppress interference. Multisensory input that is temporally or spatially coherent can attract and capture attention more effectively. Conversely, attention can selectively modulate the multisensory integration process, enabling the brain to focus on key information in complex situations.

However, most previous studies have focused on the relationship between gamma oscillations and audiovisual integration. There are still no clear conclusions about the relationship between gamma oscillations and auditory-tactile integration and how this relationship is affected by attention. Therefore, in this study, we analyzed the relationship between gamma oscillations and auditory-tactile integration under different attention conditions when the stimuli were presented in the left and right hemispaces of the body, respectively.

5.2. data preprocessing

Due to its high temporal resolution and high sensitivity, the EEG signal will contain various noises, such as common frequency interference, electromyographic artifacts, and electrocardiographic artifacts, in addition to the real signal of interest during the signal acquisition process. These noises affect the accuracy of EEG analysis, so EEG signals need to be preprocessed to remove artifacts and improve the signal-to-noise ratio.

The denoising methods used in this study mainly include filtering, independent component analysis (ICA), and extreme value removal. First, the original signal is filtered with a 0.01 Hz high-pass filter, the purpose of which is to remove signal drift caused by low-frequency interference. Then, the signal was filtered with a 100 Hz low-pass filter, which was designed to eliminate interference from high-frequency noise such as electrocardiograms and electromyograms. After that, the signal was filtered with a 60 Hz notch filter, the purpose of which was to remove interference from power frequency signals in the EEG signal.

ICA is a common and effective separation algorithm in EEG data processing. It is mainly used to decompose the observed mixed signal into several statistically independent signal components. By decoupling or decomposing the mixed signal, the originally independent source components can be estimated. ICA is often used to separate and remove interfering signals, such as eye movement artifacts (blinks or eye rotations), electromyographic artifacts, and electrocardiographic artifacts. These interferences usually have obvious temporal and spatial characteristics in the corresponding independent components, which facilitates manual or automatic identification and removal. This study is based on EEGLAB's ICA analysis of filtered data.

Extreme value removal (or thresholding) is a common artifact removal method used in the processing of electroencephalogram (EEG) data. The core idea is to use a preset amplitude or other statistical threshold to mark EEG segments that exceed the threshold range as abnormal and remove them. In this study, the amplitude threshold was set to ±80 μV. If the signal amplitude in a segment exceeds this range, the segment is discarded.

5.3. Data analysis

To investigate the relationship between gamma oscillations and auditory-tactile integration, we performed time-frequency analysis on the preprocessed EEG data. The data segment was set to -200ms~849ms. The time-frequency transformation method was Morlet wavelet transformation. The frequency range of interest was set to 30~60hz, and the time window of the wavelet transform was 3~7 cycles difference according to the frequency range. The baseline correction of the transformed data was performed using the subtraction method. Based on previous studies and our results, we selected seven electrodes (Fz, FCz, Cz, FC1, FC2, C1, C2) and a time window of 40–150 ms as the region of interest and time window. The layout of the electrodes for the region of interest is shown in Figure 5.1.

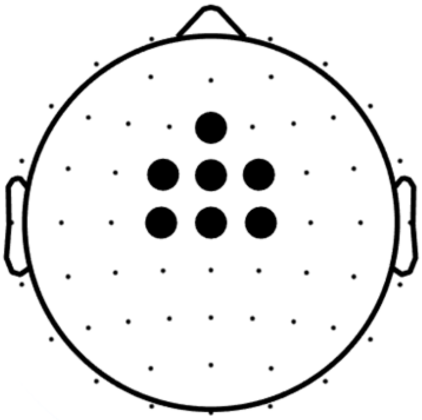

Figure5.1 Electrode position diagram

5.4. Result

In this study, the Morlet wavelet transform was used to perform time-frequency analysis on the data from each modality under each condition, and the corresponding time-frequency distributions of the evoked responses were obtained. Due to the nonlinearity of the Morlet wavelet transform, when calculating the absolute value, the tactile and auditory gamma oscillations are not simply combined linearly. Therefore, we compared the gamma oscillations of AT and A to quantify multisensory integration.

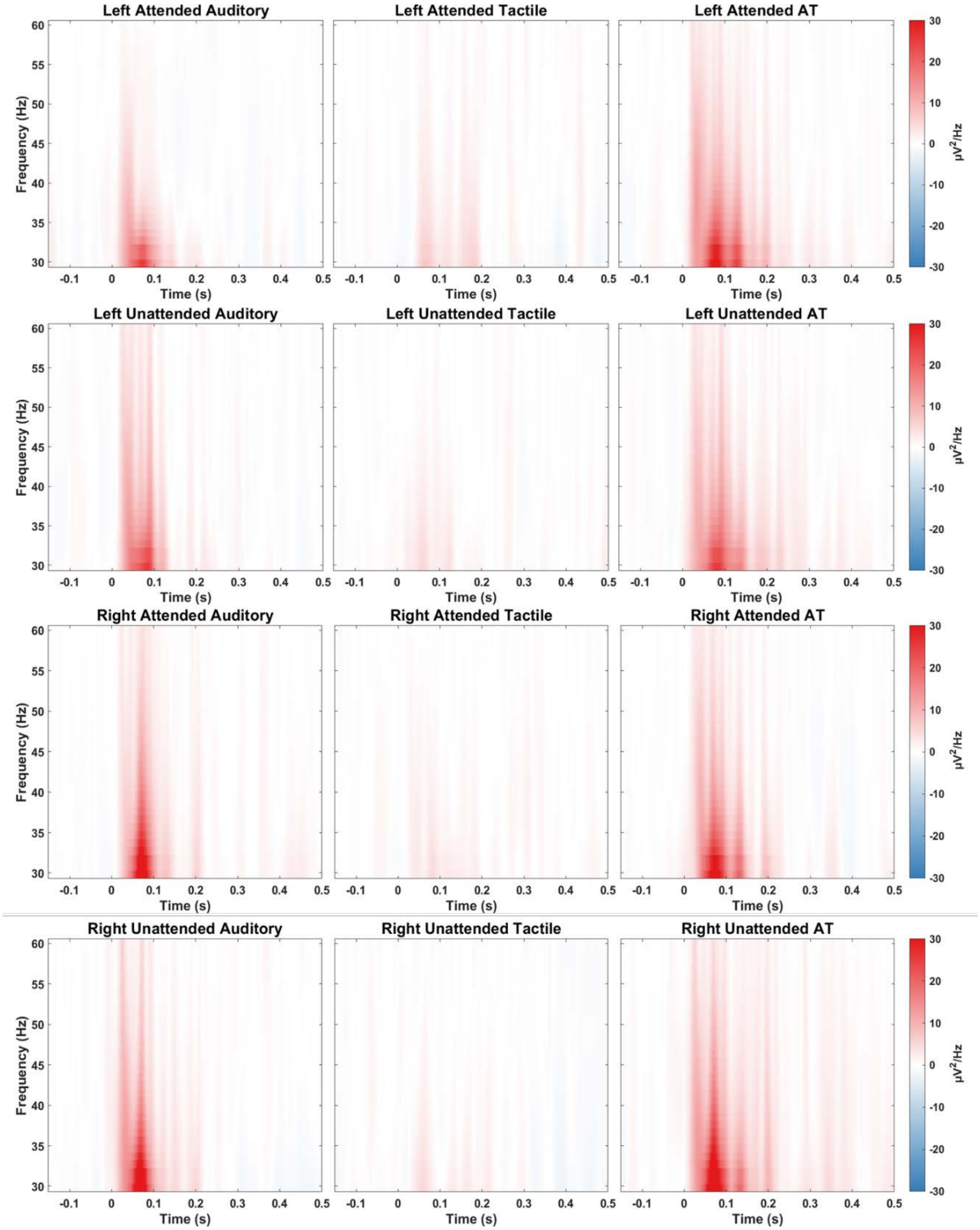

Figure 5.2 Time-frequency spectrum of gamma band

Figure 5.2 shows the gamma oscillations evoked by auditory, tactile and auditory-tactile modalities in the attended and unattended conditions. The horizontal axis indicates time, from -150 to 500 ms. The vertical axis indicates frequency, from 30 to 60 Hz. The color of each point on the plane represents the gamma oscillation energy at the corresponding time and frequency, ranging from -30 to 30 μV2.

The results showed that when the stimulus was presented in the left hemispace, the gamma oscillations induced in the unattended condition were slightly stronger than those in the attended condition, and the gamma oscillations above 40 Hz were stronger in the unattended condition. For the tactile stimulus, the gamma oscillations in the attended condition had a wider time and frequency range. For the auditory-tactile stimulus, the gamma oscillations induced by the auditory-tactile stimulus in the attended condition were stronger, and they were mainly concentrated in the range of 40–150 ms.

When stimuli are presented in the right hemispace, for auditory stimuli, the gamma oscillations induced in the attended and unattended conditions were not significantly different, with slightly more energy in the unattended condition. For tactile stimuli, the attended condition induced greater gamma oscillations. For auditory-tactile stimuli, the unattended condition induced stronger gamma oscillations.

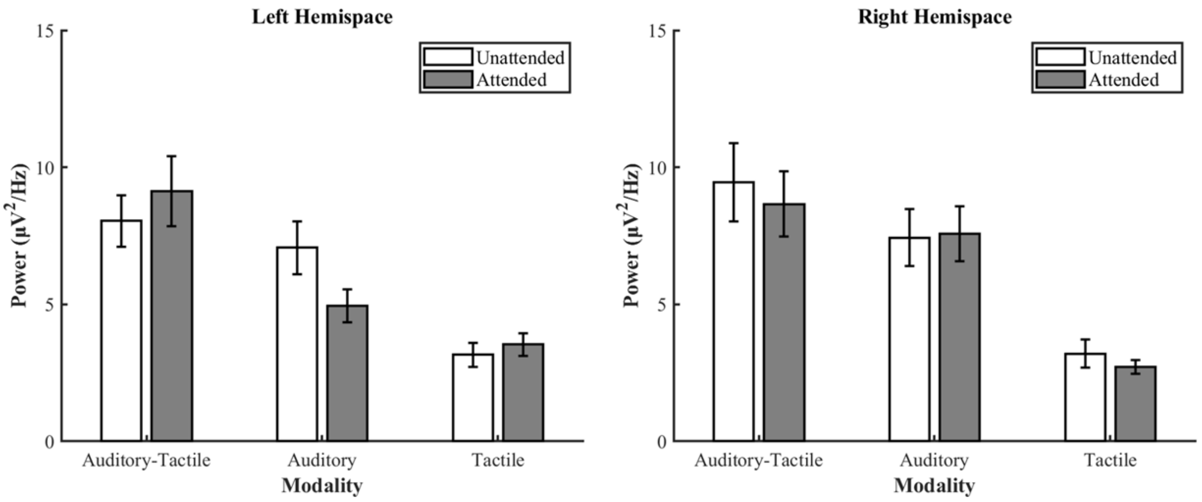

Figure 5.3 Mean values and standard error of evoked GBRs (40–150 ms after stimulus presentation) for auditory-tactile, auditory, and visual of the ROI.

As shown in Figure 5.3, we performed a 2 (attentional, non-attentional) × 3 (stimulus type: auditory, tactile, auditory-tactile) repeated-measures ANOVA on the gamma oscillations evoked by stimuli presented in the left hemispace and the right hemispace, respectively. When the stimuli were presented in the left hemispace, the results of the ANOVA showed a significant main effect of stimulus type, F (1.696, 32.223) = 32.573, $p < 0.001$, $\eta^2 p = 0.632$, suggesting that gamma oscillations evoked by different stimuli were significantly different. The interaction between attention and stimulus type was significant, F (1.625, 30.879) = 6.228, $p = 0.008$, $\eta^2 p = 0.247$.

Simple effects analyses revealed a significant difference between gamma oscillations evoked by auditory-tactile and auditory stimuli in the attention condition, $t(19)=4.633$,$p<0.001$,*Cohen's d*=1.198, with auditory-tactile stimuli evoking significantly more gamma oscillations (9.124) than auditory stimuli (4.940). There was a significant difference between gamma oscillations evoked by auditory-tactile and tactile stimuli, $t(19)=4.927$,$p<0.001$,*Cohen's d*=1.601, and gamma oscillations evoked by auditory-tactile stimuli (9.124) were significantly higher than those evoked by tactile stimuli (3.532).

In the unattended conditions, there was a significant difference between gamma oscillations evoked by auditory and tactile stimuli, $t(19)=-5.436, p<0.001$, *Cohen's* $d=-1.118$, and gamma oscillations evoked by auditory stimuli (7.062) were significantly higher than those evoked by tactile stimuli (3.158). There was a significant difference between gamma oscillations evoked by auditory-tactile and tactile stimuli, $t(19)=6.866, p<0.001$, *Cohen's* $d=1.398$, and gamma oscillations evoked by auditory-tactile stimuli (8.040) were significantly higher than those evoked by tactile stimuli (3.158). When the stimulus type was auditory, there was a significant difference between the gamma oscillations evoked by the attended and unattended conditions, $t(19)=3.373, p=0.003$, *Cohen's* $d=0.608$, and the gamma oscillations evoked by the unattended condition (7.062) were stronger than that of the attended condition (4.940). This result suggests that auditory-tactile integration was more significant in the attended condition when the stimulus was presented in the left hemispace.

When the stimuli were presented in the right hemispace, the results of the analysis of variance showed that the main effect of stimulus type was significant, $F(1.276, 24.245) = 30.365$, $p < 0.001$, $\eta^2 p = 0.615$, indicating that the gamma oscillations evoked by different stimulus types were significantly different. As the interaction between stimulus type and attention was not significant, a one-way repeated measures ANOVA was performed separately for the attended and unattended conditions.

It was found that in the attended condition, there was a significant difference in the gamma oscillations caused by auditory and tactile stimuli, $t(19)=-5.685$, $p<0.001$, *Cohen's* $d=-1.175$, indicating that the auditory stimulus caused a significantly higher gamma oscillation (7.573) than the tactile stimulus (2.705). There was a significant difference between the gamma oscillations evoked by auditory-tactile stimulation and tactile stimulation, $t(19)=5.757$, $p<0.001$, *Cohen's d*=1.437, indicating that the gamma oscillations evoked by auditory-tactile stimulation (8.659) were significantly higher than those evoked by tactile stimulation (2.705).

In the unattended conditions, there was a significant difference between the gamma oscillations evoked by auditory and tactile stimuli, $t(19)=-4.476$, $p<0.001$, *Cohen's d*=-1.022, indicating that the gamma oscillations evoked by auditory stimuli (7.437) were significantly higher than those evoked by tactile stimuli (3.204). There was a significant difference between the gamma oscillations evoked by auditory-tactile stimulation and auditory stimulation, $t(19)=2.862$, $p=0.030$, *Cohen's d*=0.484, indicating that the gamma oscillations evoked by auditory-tactile stimulation (9.442) were significantly higher than those evoked by auditory stimulation (7.437). Significant difference between the gamma oscillations evoked by the auditory-tactile stimulation and the tactile stimulation, $t(19)=4.928$, $p<0.001$, *Cohen's d*=1.506, indicating that the gamma oscillations evoked by the auditory-tactile stimulation (9.442) were significantly higher than those evoked by the tactile stimulation (3.204). This result indicates that the integration effect in the unattended condition is significant when the stimulus is presented in the right hemispace.

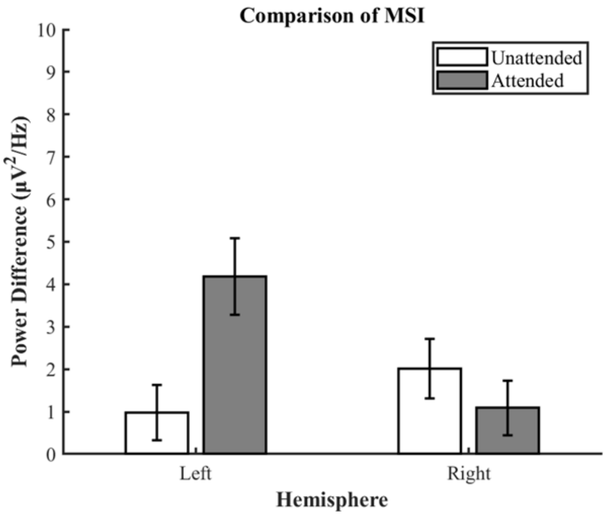

Figure 5.4 Mean values and standard error of evoked GBRs (40–150 ms after stimulus presentation) for multisensory integration comparison of the ROI.

As shown in Figure 5.4, we performed a repeated measures ANOVA with 2 (stimulus presentation position: left hemispace, right hemispace) × 2 (attention condition: attended, unattended) on the integration effect. The results showed a significant interaction between stimulus presented location and attention, $F(1, 19) = 8.152$, $p = 0.010$, $\eta^2 p = 0.300$. Simple effect analysis found that when the stimulus was presented in the left hemispace, the difference in the integration effect between the attended and unattended conditions was significant, $t(19)=-3.131$, $p=0.005$, *Cohen's d*=-0.71 5, indicating that the integration effect (4.184) in the attention condition was significantly higher than that in the non-attention condition (0.978). Under the attention condition, the integration effect of the left hemispace and the right hemispace was significantly different, $t(19)=-2.707$, $p=0.014$, *Cohen's d*=-0.691, indicating that the multisensory integration effect of the left hemispace (4.184) was significantly stronger than that of the right hemispace (1.086).

5.5. Discussion

We observed that the gamma oscillations evoked by multisensory stimulation were affected by attention beginning about 40 ms after stimuli onset, and that this effect was modulated by the spatial location of stimulus presented. When the stimuli were presented in the left hemispace, the multisensory integration effect was significant in the attended condition, while when the stimuli were presented in the right hemispace, the multisensory integration effect was significant in the unattended condition.

Whether the stimulus is presented in the left or right hemispace, compared to unimodal stimulation, multisensory stimulation always leads to an increase in gamma activity. When the stimulus is presented in the left hemispace, the increase is more significant in the attended condition, while when the stimulus is presented in the right hemispace, the increase is more significant in the unattended condition. This may reflect the amplification mechanism of gamma activity to multisensory input, and this mechanism is regulated by attention and the spatial location of stimulus presentation.

Tactile stimuli induced lower gamma oscillation compared to auditory stimuli, in both the left hemispace and right hemispace, in the attended and unattended conditions. Previous studies on audiovisual stimuli also showed a similar pattern of gamma oscillation[157]. This suggests that gamma oscillation has different patterns in different sensory modalities.

5.6. Conclusion

This study investigated the influence of attention and spatial location on auditory-tactile multisensory processing from the perspective of gamma oscillations. The results showed that when the stimulus was presented in the left hemispace, the gamma oscillations evoked by the auditory-tactile stimulus in the attended condition were significantly different from those of the unimodal stimulus. When the stimulus was presented in the right hemispace, the gamma oscillations evoked by the auditory-tactile stimulus in the unattended condition were significantly different from those of the unimodal stimulus. These results also show that the effect of auditory-tactile integration is affected by attentional resources, and this effect is modulated by the location of stimulus presentation. At the same time, gamma oscillations can be used as a powerful tool for investigating auditory-tactile integration.

6. General Conclusion and Future Projections

6.1. General discussion

This study systematically investigated the influence of attention and spatial location on auditory-tactile integration at the behavioral, event-related potential (ERP), and neural oscillation levels. Overall, our results not only demonstrated that auditory-tactile integration can occur in both left and right hemispaces but also indicated an interaction between spatially selective attention and stimulus presented location: in the left hemispace, attention accelerates and strengthens auditory-tactile integration; in the right hemispace, however, integration occurs earlier and more significantly in unattended conditions.

First, at the behavioral level, responses to auditory stimuli were significantly faster than those to stimuli from a unimodal modality, which is in line with previous research findings that multisensory stimuli can lead to performance gains. Notably, comparisons between the left and right hemispaces showed that although auditory-tactile integration effects could be observed in both sides, results from the competitive model analysis showed that integration occurred earlier and lasted longer in the left hemispace. Due to possible functional asymmetries in the brain's processing of the left and right hemispaces of the body (e.g., the right hemisphere is more biased towards spatial attention processing, while the left hemisphere is associated with language or higher cognition, etc.), it is speculated that tactile and auditory information from the left hemispace may have a higher processing priority in certain neural pathways, thereby making the tactile-auditory multisensory enhancement more pronounced when the stimulus is presented on the left side.

Secondly, the ERP results further support the above behavioral findings: ERP waveform differences related to auditory-tactile integration can be observed regardless of whether the left or right hemispace is stimulated. However, the effect of attention on the time window in which integration occurs and the spatial extent of brain activation showed significant spatial dependence. In the left hemispace, integration in the attended condition occurred in an earlier time window of 70–90 ms and was more widely distributed. In the right hemispace, on the contrary, integration effects first appeared in the time window of 110–130 ms in the unattended condition. This shows that the modulatory effect of attention on different spatial information is not simply “uniform enhancement” or “uniform inhibition”, but interacts with the spatial location of the stimulus: when the stimulus is presented on the left, the addition of attention resources can effectively accelerate and expand integration; when the stimulus is presented on the right, integration seems to be more dependent on bottom-up automatic processing pathways. Attention does not significantly promote the early integration of right hemispace but rather shows signs of integration in a later window of 180 to 220 milliseconds.

Finally, the results observed from the perspective of neural oscillations also indicate that auditory-tactile integration was influenced by the interaction of attention and spatial location. Previous multisensory studies indicated that the gamma band is deeply related to perceptual integration and attentional selection. This study found that multisensory stimulation in the left hemispace induced a stronger gamma response under attended conditions, while multisensory gamma responses were more significant for stimuli in the right hemispace under unattended conditions. This phenomenon was consistent with the ERP findings and further demonstrated that the brain's processing of the external environment is not determined by a single factor of “whether attention is given” but also related to the position of the stimulus itself in spatial or somatic coordinates. The neural network connections and resource allocation patterns between different spatial hemispheres may make it easier for left stimuli to gain integration gains under top-down attention mechanisms, while right stimuli may be more sensitive to triggering involuntary attention or automatic integration processes in bottom-up pathways.

The above findings have the following insights for the study of the neural mechanisms of multisensory integration: First, traditional multisensory integration research has often focused on audio-visual integration, with less attention paid to auditory-tactile integration. This study fills this gap by discovering that auditory-tactile integration is also influenced by attention and spatial factors. Second, attention does not simply “facilitate” or “enhance” integration in all spatial conditions. There is also a certain lateralization effect and spatial position dependence. Third, the results of this study imply that dorsal pathways (related to spatial orientation) and ventral pathways (related to target recognition or object feature processing) may have different weights in the early and late stages of the auditory-tactile information flow. This provides new ideas for further understanding the division of labor between the left and right hemispheres in multisensory processing.

6.2. General conclusion

This study systematically investigated the integration process of auditory and tactile stimuli in the left and right hemispaces and its dependence on attentional modulation. Based on behavioral measures, event-related potentials, and gamma band neural oscillation analyses, our findings are as follows.

Both auditory and tactile stimuli in the left and right hemispaces could be significantly integrated. Left hemispace stimuli showed earlier and stronger integration under attended conditions, while right hemispace stimuli showed earlier and more prominent integration effects in the unattended conditions. This difference in the integration time course and brain activation patterns was further confirmed by gamma band oscillations. The above results highlight the obvious lateralized differences in the modulation of spatial selective attention on multisensory integration. Combined with existing research on multisensory integration and attention mechanisms, it can be hypothesized that the brain's processing of external information is a dynamic process shaped by multiple factors such as spatial location, attentional status, and sensory modality.

This study is of great theoretical significance for understanding the neural mechanisms of auditory-tactile integration and how attention regulates this integration. It also provides new ideas and possibilities for future applications of the principles of auditory-tactile integration in fields such as clinical rehabilitation, sensory substitution, and human-computer interaction.

6.3. Future Projections

This study mainly used ERP and time-frequency analysis to investigate the temporal window and spatial distribution of integration. In the future, neuroimaging techniques with higher spatial resolution (e.g., functional magnetic resonance imaging, fMRI) or brain stimulation techniques (e.g., transcranial magnetic stimulation, TMS) can be combined to further explore the causal relationships of related brain areas.

In addition, individual differences in participants (e.g., left- or right-handedness, gender differences, sensory sensitivity) and stimulus factors (type of tactile stimulus, intensity and frequency of auditory stimuli, etc.) may also affect the integration process and should be verified in larger samples and more task contexts.

Finally, this study focused on the spatial and attentional regulation of external stimuli. How to combine these findings with more practical applications, such as tactile feedback to enhance auditory perception in patients with hearing impairments or multisensory interaction in virtual reality, is a research direction with future application value.

Publications

[1] **An, W.,** Zhang, N., Li, S., Yu, Y., Wu, J. and Yang, J., 2024. The Impact of Selective Spatial Attention on Auditory–Tactile Integration: An Event-Related Potential Study. Brain Sciences, 14(12), p.1258.

[2] Zhang, N., **An, W.,** Yu, Y., Wu, J. and Yang, J., 2024. Go/No-Go Ratios Modulate Inhibition-Related Brain Activity: An Event-Related Potential Study. Brain Sciences, 14(5), p.414.

[3] Ren, R., **An, W.,** Yu, Y., Tang, X., Ejima, Y., Wu, J. and Yang, J., 2024. Tactile temporal predictions: The influence of conditional probability. i-Perception, 15(4), p.20416695241264736.

[4] Wang, B., Yang, L., Yan, **W., An**, W., Xiang, J. and Li, D., 2023. Brain asymmetry: a novel perspective on hemispheric network. Brain Science Advances, 9(2), pp.56-77.

[5] **Weichao An**, Yinghua Yu, Yoshimichi Ejima, Satoshi Takahashi, Jinglong Wu, Jiajia Yang. Spatial attention can modulate audio- tactile integration： an ERP study. (CME 2024)

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