

Psychophysiological Mechanisms of Melody Perception and Internal Repetition in Healthy Individuals and Schizophrenia

Alexander V. Vartanov¹ , Veronika M. Zubko¹ , Vasilisa D. Abrosimova¹ ,
Mariia D. Krysko² , Daria A. Leonovich³ , Olga V. Shevaldova^{4*} 

¹ Lomonosov Moscow State University, Moscow, Russian Federation

² Russian State University for the Humanities, Moscow, Russian Federation

³ Russian Presidential Academy of National Economy and Public
Administration, Moscow, Russian Federation

⁴ Federal Research Center for Innovative and Emerging Biomedical and
Pharmaceutical Technologies, Moscow, Russian Federation

*Corresponding author: shevaldova_ov@academpharm.ru

Abstract

Introduction. The study investigates the psychophysiological mechanisms of melody perception and internal repetition in healthy individuals and patients with schizophrenia. The study primarily focuses on differences in neural processing of monophonic and polyphonic musical stimuli, providing deeper insight into the cognitive and neural features associated with schizophrenia. **Methods.** The study involved 53 female participants divided into two groups: 25 patients diagnosed with schizophrenia (F20 according to ICD-10) and 28 healthy volunteers. Brain activity was recorded using 19-channel EEG, followed by data processing with the "Virtual Implanted Electrode" method, which allowed for the analysis of activity and functional connectivity in 53 brain structures. Participants performed a task involving the extraction and internal repetition of a monophonic line from polyphonic musical stimuli. **Results.** The experiment revealed that in healthy individuals, activation occurs in visual areas, the supramarginal gyrus, and the right basal ganglia, ensuring accurate internal reproduction of the musical motif. In schizophrenia, weakened connectivity was observed in the left supramarginal gyrus, along with heightened activity in areas associated with polyphony perception, indicating

difficulties in maintaining and reproducing relevant musical components. **Discussion.** The findings demonstrate differences in the neural mechanisms of musical stimulus processing in schizophrenia. Weakened connectivity in control areas and heightened activity in perception regions may explain difficulties in accurate melody reproduction. The results highlight the role of subcortical structures in compensatory processes and open new avenues for research into cognitive impairments in schizophrenia.

Keywords

melody perception, internal melody repetition, schizophrenia, reconstructed electrical activity

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Introduction

The internal representation of melodies, as part of inner speech, plays a key role in human cognitive processes. This topic has attracted scientific interest due to its complexity and importance in understanding brain mechanisms, particularly in the context of various mental disorders such as schizophrenia. A distinctive feature of music as a means of communication is that its psychophysiological, somatic, and subjective experience remains independent of the cultural backgrounds of performers and listeners, despite music itself being a cultural product (Putkinen et al., 2024). The mechanisms of music perception have traditionally been associated with right-lateralized activity in the temporal lobe, including the superior temporal gyrus, Heschl's gyrus, insular cortex, and striatum (Fujito et al., 2018). However, the psychophysiological mechanisms of music perception depend on the listener's familiarity with a given composition. A 2023 meta-analysis by Canadian researchers (Vuong et al., 2023) revealed distinct neural networks underlying the perception of familiar versus unfamiliar melodies. When processing familiar melodies, activation occurs in a left-lateralized cortico-subcortical network comprising three key

clusters: the supplementary motor area (Brodmann area 6), the inferior frontal gyrus (IFG, including area 44), and the insular cortex. The involvement of these regions has been interpreted within the framework of predictive coding theory, which posits the generation of hypotheses and their validation through comparison with sensory input. Musical stimuli are frequently used as models for studying neural networks within this theoretical framework (Olszewska et al., 2023; Senn, 2023). Most people have experienced the phenomenon of perceiving a familiar melody even when it is not actually playing (Liikkanen, 2008), but rather being mentally recalled (Gabriel et al., 2016)—a phenomenon known as musical imagery. These internal representations facilitate the prediction of melodic continuations (Eggermont, 2023), which may explain the overlapping neural structures involved in both perception and imagination of melodies (Gabriel et al., 2016). Internal melody repetition refers to the process in which a person mentally reproduces heard music without any external auditory stimulus. This process engages multiple cognitive functions, including attention, working memory, perception, and planning. Research indicates that the internal representation of melodies activates brain regions similar to those involved in actual music perception and production, such as the primary auditory cortex, premotor, and motor areas (Zatorre & Halpern, 2005). The processing and mental representation of melodies involve both cerebral hemispheres. Bilateral activation has been observed during interaction with familiar melodies accompanied by lyrics (Zatorre et al., 1996). For purely instrumental stimuli, greater right-hemisphere dominance has been reported (Halpern et al., 2004), whereas other nonverbal stimuli have elicited left-hemisphere activation without corresponding right-hemisphere engagement (Kraemer et al., 2005).

Electroencephalography (EEG) is one of the primary methods for investigating brain activity during the internal representation of melodies. This technique records the brain's electrical activity with high temporal resolution, making it particularly valuable for studying rapid cognitive processes. Research indicates that internal melody reproduction is associated with modulations in EEG alpha and beta rhythms. For instance, increased alpha rhythm amplitude (8–12 Hz) correlates with enhanced attention and concentration during mental music rehearsal (Schaefer et al., 2011). Meanwhile, beta rhythm fluctuations (13–30 Hz) may reflect activation in motor and premotor cortical areas, which are involved in planning and simulating movement sequences related to instrumental performance (Bhattacharya & Petsche, 2005).

Schizophrenia is one of the most complex mental disorders, characterized by impairments in thought processes, perception, and emotional regulation. A hallmark symptom of schizophrenia is auditory hallucinations, which frequently involve internal voices or sounds. These hallucinations may arise from disruptions in inner speech and the neural representation of auditory stimuli. Research indicates that patients with schizophrenia exhibit deficits in cognitive functions such as working memory and attention, which may impair their ability to mentally reproduce melodies (Ford & Mathalon, 2004). EEG studies in schizophrenia patients reveal abnormalities across multiple frequency bands, including reduced alpha rhythm power and increased delta

rhythm power (1–4 Hz). These alterations suggest impairments in cognitive processing and auditory perception (Uhlhaas & Singer, 2010). Such anomalies may reflect disrupted neural synchronization, compromising the efficient generation of inner speech and melodic representations.

Studies show that the internal representation of polyphonic melodies, consisting of multiple independent lines, requires higher cognitive resources compared to monophonic melodies. This is due to the need to simultaneously maintain and process multiple auditory stimuli, which complicates the process of internal reproduction (Deutsch, 1999). In patients with schizophrenia, this task may cause even greater difficulties due to deficits in cognitive processes such as attention and working memory.

Understanding the psychophysiological mechanisms of internal melody repetition may have important practical applications. For example, results of such studies could be used to develop new diagnostic and therapeutic methods for schizophrenia aimed at improving cognitive functions and reducing symptoms (Ford & Mathalon, 2004). Furthermore, data on internal melody representations may be useful for developing brain-computer interfaces that would enable people with disabilities to interact more effectively with their environment (Minguillon et al., 2017).

Thus, the study of internal melody repetition in healthy individuals and in schizophrenia represents an important direction in neuroscience and psychophysiology. It provides better understanding of brain mechanisms related to cognitive and emotional processes, and enables development of new diagnostic and therapeutic approaches for mental disorders.

Objective: To investigate the specificity of psychophysiological mechanisms underlying melody perception and internal repetition through comparison of healthy controls and schizophrenia patients.

Object of Study: Characteristics of polyphonic stimulus representation in healthy individuals and schizophrenia patients.

Subject of Study: Psychophysiological mechanisms of internal representation processes for polyphonic stimuli in healthy individuals and schizophrenia patients.

Hypothesis: The internal representation of polyphonic and monophonic auditory stimuli involves subcortical nuclei that provide core representation mechanisms, which remain less impaired in schizophrenia.

Methods

Sample

The study involved 53 female participants divided into two groups. The clinical group comprised 25 inpatients from Psychiatric Clinical Hospital No. 1 named after

N.A. Alekseev with schizophrenia spectrum disorders (ICD-10 code F20), presenting verbal pseudohallucinations and abstract thinking difficulties (mean age: 41 years). The control group consisted of 28 healthy volunteers without psychiatric or neurological disorders, all right-handed (mean age: 37 years). All clinical group patients were under long-term antipsychotic medication. Participants provided written informed consent after reviewing the study protocol. The study was approved by the Bioethics Committee of Psychiatric Clinical Hospital No. 1 named after N.A. Alekseev.

Equipment

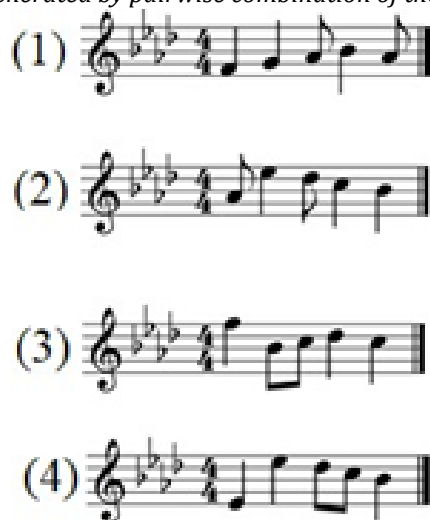
EEG recordings were obtained from 19 channels according to the international 10-20 system using a Neuro-KM electroencephalograph (sampling rate: 1000 Hz, bandpass filter: 0.3-30 Hz). Primary EEG data processing was performed using licensed BrainSys software.

Stimuli

The stimulus set included recordings of 4 melodies and their combinations forming polyphonic stimuli. The melodies were composed such that simultaneous playback created harmonic fugue structures. Each melody was performed on two instruments: piano and glockenspiel. Polyphonic structures were created by pairing melodies with different instruments and distinct melodic patterns. Additionally, melodies were combined with word recordings to create verbal-melodic composite stimuli. The monophonic melodic constructions used for stimulus generation are presented in Figure 1.

Figure 1

Musical notation of stimulus materials. Each staffline displays a monophonic melodic construction. Polyphonic structures are generated by pairwise combination of these lines.



Research Procedure

Participants underwent briefing where the study objectives and procedures were explained, after which they signed informed consent forms. Their task was to listen to and identify a melodic line performed on piano, then mentally repeat it following a conditional signal. All stimuli were delivered through headphones. EEG recordings were obtained during the experimental sessions. Participants completed all trials with closed eyes to minimize eye movement and blink artifacts. They were also instructed to remain motionless during recordings.

Data Processing and Analysis Methods

The obtained data consisted of EEG recordings. The first processing stage involved visual artifact inspection (including eye movements) using Brainsys (BrainWin) software. Next, artifacts related to electrical equipment at 50 Hz frequencies were removed.

Subsequent analysis calculated localized activity in predetermined brain regions of interest using the novel "Virtual Implanted Electrode" method developed by A.V. Vartanov (Russian Patent No. 2 785 268). The algorithm is described in (Vartanov, 2022). Unlike existing approaches based on dipole models (which effectively describe high-frequency EEG components - gamma rhythms), this method utilizes a unipolar model (non-directional spatial charge) originating not from postsynaptic potentials but from afterpotentials reflecting active ion transport processes for neuronal membrane potential restoration (whose random summation explains low-frequency EEG components) (Masharov, 2019). The method has been validated through deep brain stimulation studies (Vartanov, 2023). The analysis examined activity and functional connectivity across 53 brain structures: hypothalamus, pons, midbrain, medulla oblongata, caudate nuclei (L, R), medial globus pallidus (L, R), putamen (L, R), thalamus (L, R), hippocampus (L, R), amygdala (L, R), ventral anterior cingulate cortex (BA24), dorsal anterior cingulate cortex (BA32), insular cortex (L, R), ventral striatum (BA25), dorsolateral prefrontal cortex (BA9: L, R), supramarginal gyrus (BA40: L, R), parietal cortex (BA7: L, R), Broca's area and its homolog (BA44: L, R), Wernicke's area and its homolog (BA22: L, R), cerebellum (L, R), angular gyrus (BA39: L, R), middle frontal gyrus (BA10: L, R), orbitofrontal gyrus (BA47: L, R), parahippocampal gyri PHC1 and PHC2 (L, R), visual areas (L, R): V1 (BA17), V4, V3v, VO1, VO2.

Using this technology, averaged evoked potentials (EPs) were obtained for each of the 53 brain structures (time-locked to stimulus presentation and internal repetition cues) spanning 200 ms before to 500 ms after events across four experimental conditions. Connectivity graphs were constructed by calculating correlations between EPs in these structures and visualized using GraphViz 2.38 software.

Each graph additionally reflects amplitude and temporal characteristics of evoked potentials across structures under experimental conditions. This approach reveals similarities and differences in functional connectivity patterns involved in the studied

cognitive process. Connection characteristics included: strength (connectivity correlation coefficient), directionality (unidirectional or bidirectional), and type (excitatory or inhibitory). In this study, connectivity was defined as synchronization of EP temporal and amplitude characteristics. Graph descriptions include correlation coefficients: positive values indicate excitatory connections, negative values indicate inhibitory connections. Strong connections were defined as those with correlation coefficients exceeding 0.70. Connections with coefficients between 0.40-0.60 were considered weak and potentially random, and therefore might be excluded from the studied network.

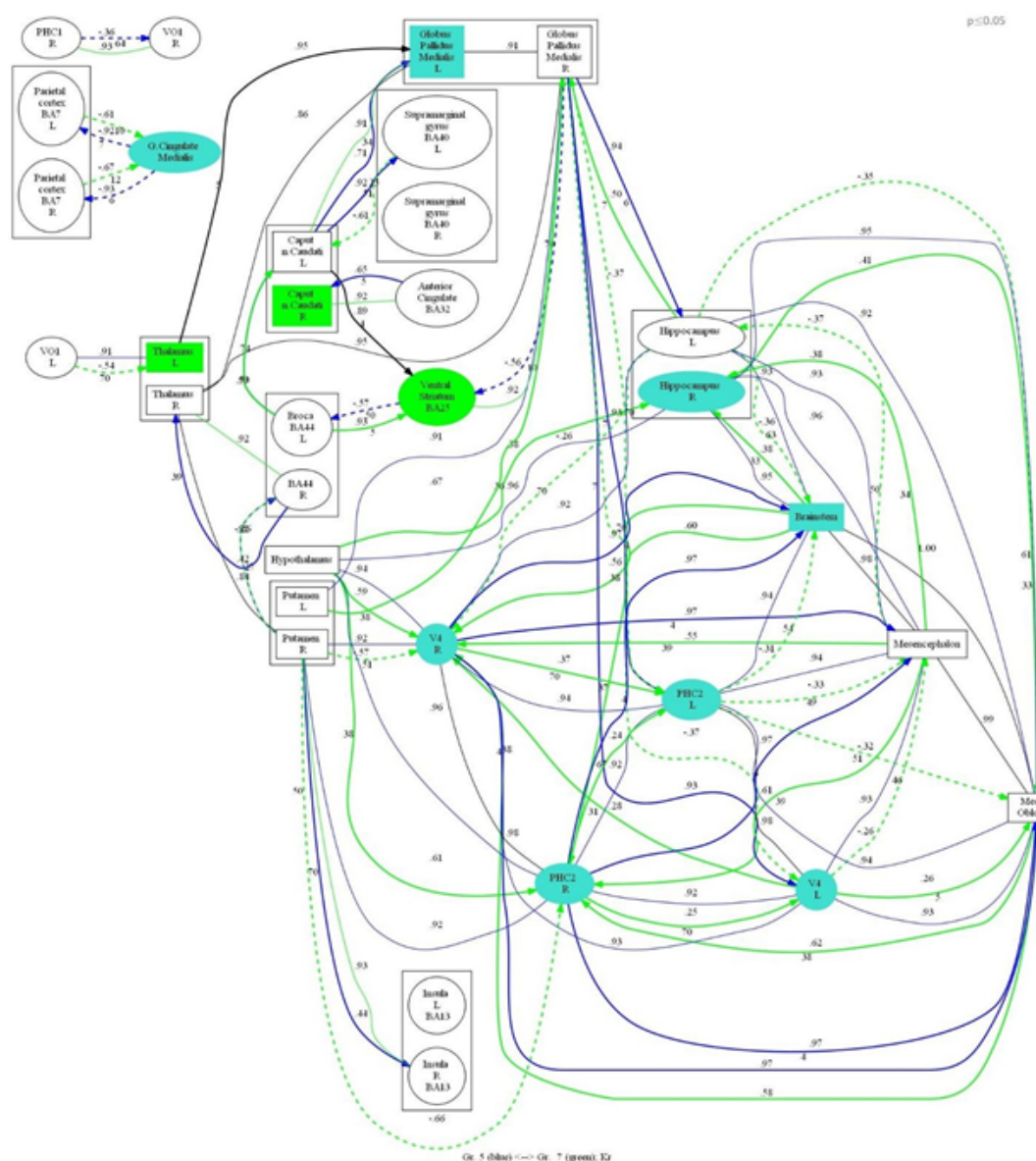
Results

The presented figures illustrate both common and distinct psychophysiological mechanisms underlying different aspects of internal representation for monophonic and polyphonic auditory stimuli. Black connections represent connections identical in strength, direction, and type across both compared groups/conditions. Blue or green connections indicate differences in these parameters, serving as basis for interpreting impairment mechanisms affecting internal representation generation/reproduction (in between-group comparisons). Colored structures denote structures with maximum amplitude values within each condition/group. Yellow structures mark where peak amplitude values were characteristic for both conditions/groups. Blue or green structures: Indicate structures with peak amplitude specific to one condition/group.

The connectome shown in Figure 2 demonstrates that during the perception and extraction of monophonic melodic lines from polyphonic stimuli, no brain structures exhibited equally high amplitudes in both groups. In the clinical group, the most active structures were the left thalamus, right caudate nucleus and ventral striatum, while in the control group - the ventral part of the anterior cingulate gyrus, left globus pallidus, right hippocampus, brainstem, and bilateral visual areas PHC2 and V4.

Common connections in both groups. High correlation coefficients are observed in subcortical structures: between the right thalamus and right putamen (0.84), as well as the right (0.95) and left (0.86) globus pallidus, between which a strong connection was also found (0.91). Common excitatory connections are also observed from the left thalamus to the left globus pallidus (0.95) and from the right caudate nucleus to the ventral striatum (0.89). A still strong connection (0.98-1.00) exists between brainstem structures. In the cortex, equally strong connections in both groups were found between visual regions PHC2 and V4 in the right (0.96) and left (0.97) hemispheres.

Connectome for perception and extraction of monophonic melodic lines from polyphonic musical images



Note. Blue indicates structures and processes most active in the control group. Green marks structures and processes most active in the clinical group. Yellow designates structures most active in both groups. Connection line styles: Solid lines represent excitatory processes. Dashed lines indicate inhibitory processes. The figures also display correlation coefficients for functional connectivity measures.

Differences in connections between groups. During interaction with polyphonic musical stimuli, strengthening of some connections is observed in the clinical group. A weak inhibitory connection between right PHC1 and VO1 in controls (-0.36) becomes strengthened (0.93) in schizophrenia and loses its inhibitory properties. Connections also strengthen between right globus pallidus and ventral striatum (0.92), left globus pallidus and left caudate nucleus (0.93), between dorsal anterior cingulate cortex and right caudate nucleus (0.92), right insula and right putamen (0.93), right thalamus and area 44 (0.92). In the control group, these connections are weaker, with particularly significant differences observed in right insula-putamen connections (0.44 in control group), right thalamus-area 44 connections.

Broca's area connectivity differences show distinct patterns. During monophonic melody perception and extraction, controls demonstrate inhibitory connections from right globus pallidus (-0.56) through ventral striatum (-0.57), though these connections remain relatively weak. In contrast, the clinical group exhibits strong excitatory connections originating from Broca's area to bilateral globus pallidus via left caudate nucleus (0.99) to left (0.91) and through ventral striatum (0.93) to right (0.92) structures. No connection between Broca's area and caudate nucleus was found in controls.

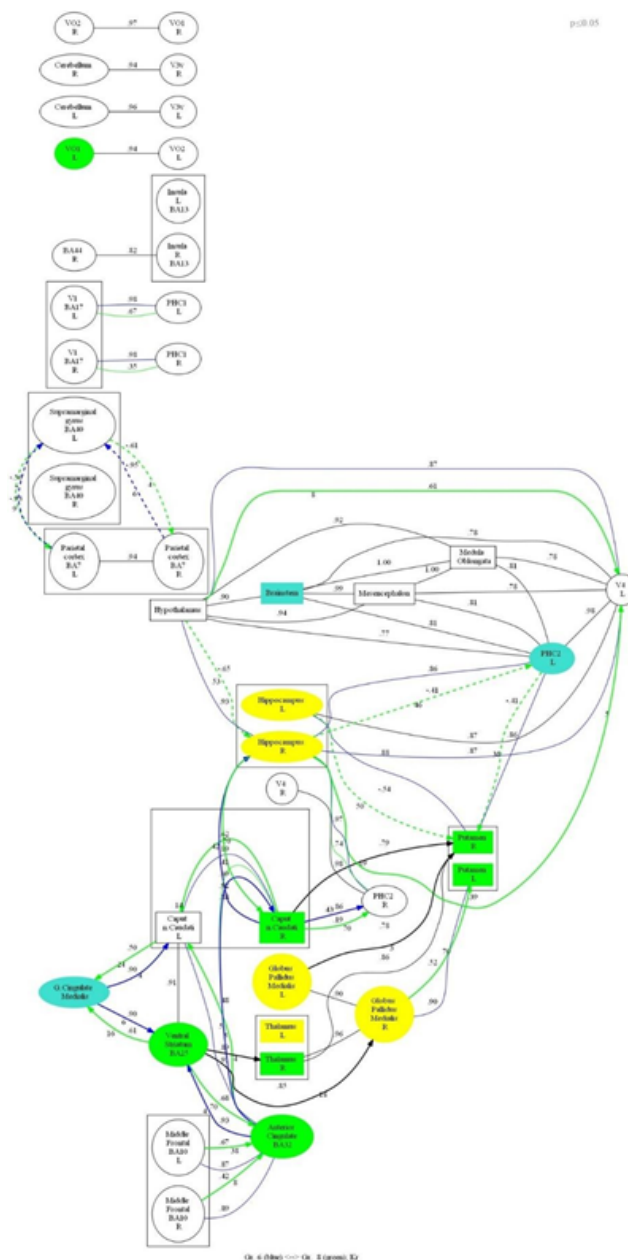
Strongest connections in controls appear between ventral cingulate cortex and parietal regions (R -0.93; L -0.92), left thalamus and left VO1 (0.91), right globus pallidus and V4 (0.93). Interhemispheric connections between visual regions and brainstem structures (0.93-0.99) were observed, along with an excitatory ascending pathway between right putamen and PHC2 (0.92). These connections appear significantly weakened in the clinical group.

While both groups maintain relatively strong connectivity between right hippocampus and hypothalamus (controls: 0.96; clinical: 0.92), the clinical group lacks excitatory hypothalamic projections present in controls, where this process shows bidirectional connectivity.

During the internal representation of a single melodic line from a polyphonic image, the most active structures in both groups are the bilateral globus pallidus and hippocampus, as well as the left thalamus. In the control group, the most active structures are the ventral part of the cingulate gyrus, brainstem, and left PHC2. In the clinical group, the highest amplitude values are observed in the right thalamus and caudate nucleus, ventral striatum, dorsal part of the anterior cingulate cortex, as well as bilateral putamen.

Figure 3

Connectome for internal representation of monophonic melody extracted from polyphonic musical image



Note. Structures and processes most active in the control group are marked in blue; in the clinical group – in green; structures most active in both groups – in yellow. Solid lines indicate excitatory processes, dashed lines – inhibitory processes. Correlation coefficients for functional connectivity measures are also shown.

Common connections in both groups. Strong connections were found between visual areas VO1 and VO2 in the right hemisphere (0.97), as well as between the cerebellum and region V3v on the right (0.94) and left (0.96). Strong common connections are also observed between PHC2 and V4 in the left hemisphere (0.98), with V4 in turn connected to the left hippocampus (0.87). Strong connections were also recorded between the insular cortex and area BA44 in the right hemisphere (0.82), between brainstem structures with each other (0.99-1.00), as well as between left and right parietal cortex (0.94). Common connections were also found between brainstem structures and left PHC2 (0.81), as well as with the hypothalamus (0.90). Strong connections are also observed between PHC2 and V4 in the left hemisphere (0.98). Excitatory connections can be noted from the left-hemisphere globus pallidus to the right-hemisphere putamen (0.78). Strong connections are also observed between the ventral striatum and left caudate nucleus (0.91), as well as connections activating the right globus pallidus (0.93) and right thalamus (0.89), which is connected to the right globus pallidus (0.96) and putamen (0.86). The right caudate nucleus activates the right putamen (0.79).

Differences in connections between groups. In the clinical group compared to controls, no strengthening of connections is observed - all connections are significantly weaker, and for some connections their nature and direction change. Only weakening was recorded in connections between area V1 and PHC1 in both hemispheres, with the weakening being stronger in the right hemisphere (0.35/control 0.98) than in the left (0.67/control 0.98), as well as the excitatory connection from the caudate nucleus to region PHC2 in the right hemisphere. Differences in the nature of connections are observed between the hypothalamus and right hippocampus, as well as between the left hippocampus and right putamen. In the control group, a bilateral excitatory connection was noted (0.93), while in the clinical group, inhibition is directed toward the hippocampus (-0.65). The connection between the left hippocampus and right putamen in the control group is represented as bilateral excitatory (0.88), while in the clinical group it is weakened (-0.54) and transmits inhibition to the putamen.

In this task, quite many intergroup differences are observed, characterized by weakening of connections in the clinical group and reversal of their direction of excitation and inhibition transmission. For example, normally there is an inhibitory connection directed toward the left supramarginal gyrus from the left (-0.93) and right (-0.95) parietal cortex, while in the clinical group the inhibitory connections are significantly weaker and directed from the left supramarginal gyrus toward the right (-0.56) and left (-0.61). A similar trend is observed in parts of the cingulate cortex. In the control group, there is an excitatory connection toward the left caudate nucleus (0.90) and ventral striatum (0.90), while in the clinical group these structures transmit excitatory signals toward the cingulate gyrus, also with weakening (0.61 from striatum, 0.50 from caudate nucleus). The dorsal part of the cingulate gyrus also activates excitatory connections toward the ventral striatum (0.93), left (0.87) and right (0.89) middle prefrontal cortex, as well as toward the left caudate nucleus (0.91).

Similar differences are observed in the connectivity between right and left caudate nuclei: in the control group the connection is bilateral (0.89), while in the clinical group excitation is directed to the left hemisphere, with the connection weakened (0.62). The connection between hypothalamus and region V4 in the left hemisphere: bilateral connection in the control group (0.87), in the clinical group a weakened excitatory connection is directed toward the visual region in the left hemisphere (0.61), while the connection between hypothalamus and right hippocampus in the control group shows a bilateral connection (0.93), whereas in the clinical group it acquires an inhibitory character from the hypothalamus toward the hippocampus (-0.65).

Discussion

The polyphonic musical structure has several differences from monophonic verbal stimuli. First, it does not require semantic processing and can trigger affective reactions. At the same time, it allows selecting which line will be dominant at a given moment (Huberth & Fujioka, 2017). In this experiment, the experimenter explicitly instructed participants to choose the dominant line, and the obtained results reflect the process of maintaining attentional focus on the target line.

In this process (Fig. 2), stronger preserved connections are observed in the clinical group, including connections between visual areas (encoding color and general scene), as well as between thalamus and basal ganglia, and between caudate nucleus and striatum. These connections have been repeatedly demonstrated in healthy groups regarding the link between musical perception and color perception (Palmer et al., 2013), while the thalamus-basal ganglia connection is involved in attentional focus (Smith, 2022).

Compared to controls, the clinical group shows strengthened connections between visual areas (form and scene), Broca's area with caudate nucleus and striatum (which excites globus pallidus). These findings may indicate a process shifted toward inner speech rather than internal representation. This interpretation is supported by connections of speech-generating structures, such as motor components with globus pallidus (Bakhtin et al., 2020), as well as sound scene integration through putamen-insula connections. Strong connections between thalamus and right-hemisphere area 44, and between Broca's area, caudate nucleus and striatum may reflect use of subvocalization mechanisms to maintain attention on the target line (Vuong et al., 2023).

In controls, there is a tendency for activation of visual regions and supramarginal gyrus activity supporting stimulus interpretation. Visual areas create associative patterns linked to sound movements, so the image is recoded into polymodal visuo-spatial-auditory (rather than verbal) form, enabling accurate motif reproduction (Kholikov, 2023).

The part of the study shown in Fig. 3 differs in that during mental rehearsal, participants had to not simply reproduce the original stimulus automatically, but transform it - extract an internal representation of its part (associated with a specific instrument's sound)

and reproduce precisely that. Common strong connections remain between right basal ganglia structures, possibly supporting nonverbal inner speech (Riva et al., 2018), consistent with fMRI findings (Krysko, Vartanov, Bronov, 2024). Also aligning with fMRI data are cerebellar-occipital connections and right-hemisphere area 44-insula links supporting musical syntax processing (Maess et al., 2001; Kunert et al., 2015; Chiang et al., 2018).

Key differences include weaker left supramarginal gyrus connectivity and hippocampal inhibitory connections in schizophrenia. This may reflect failure to maintain target figures in working memory while potentially retaining/excluding irrelevant components as a compensatory mechanism in chronic illness (Sass & Parnas, 2007). While thalamic connections with putamen, globus pallidus and striatum remain preserved, subcortical-cortical connections are markedly weakened in schizophrenia. This may indicate unconscious extraction of relevant components by excluding irrelevant ones, whereas healthy processing involves conscious foreground-background separation of task-relevant streams (Uhlir, Fairhurst & Keller, 2013). Schizophrenia patients may have selected perceptually dominant rather than task-relevant components, evidenced by enhanced activation in standard polyphony perception zones but weakened control regions (Dutterer et al., 2023).

Thus, during attentional focus on a polyphonic melody line, healthy individuals activate visual regions and supramarginal gyrus enabling precise internal reproduction of instrument-specific components. In schizophrenia, weakened left supramarginal gyrus connectivity and retention of irrelevant components affects internal reproduction, possibly reflecting compensatory mechanisms. Enhanced activity in polyphony perception zones co-occurs with weakened control regions.

Conclusions

Under normal conditions, when focusing on the dominant line of a polyphonic stimulus, activation occurs in visual areas, the supramarginal gyrus, and regions associated with musical syntax. This ensures accurate internal reproduction of the musical motif associated with a specific instrument. Strong connections exist between the right basal ganglia, thalamus, and other structures, supporting the mechanism of subvocalization and attentive perception of musical elements. In individuals with schizophrenia, weakened connections are observed between the left supramarginal gyrus and other areas, along with enhanced activity in regions associated with polyphony perception. This may indicate difficulties in maintaining and internally reproducing relevant musical components, as well as compensatory mechanisms aimed at managing irrelevant information. Under schizophrenic conditions, weakened connections in control areas and enhanced activity in polyphony perception regions may lead to impaired accuracy of internal reproduction and extraction of the dominant line. This supports the hypothesis that schizophrenia affects cognitive processes related to musical perception and internal reproduction.

Thus, the study reveals differences in neural connections and brain region activation during polyphonic music perception between healthy individuals and patients with schizophrenia. Under normal conditions, the processes of focusing and internal reproduction occur more efficiently, whereas in patients with schizophrenia, impairments in these processes are observed, which may be associated with compensatory mechanisms and alterations in musical information processing.

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Author Contributions

Alexander V. Vartanov – participation in the development of the research concept, data collection and analysis, discussion of the results, preparation of the manuscript.

Veronika M. Zubko – participation in the development of the research concept, data collection and analysis, discussion of the results, preparation of the manuscript.

Vasilisa D. Abrosimova – participation in the development of the research concept, data collection and analysis, discussion of the results, preparation of the manuscript.

Mariia D. Krysko – participation in the development of the research concept, data collection and analysis, discussion of the results, preparation of the manuscript.

Daria A. Leonovich – participation in the development of the research concept, data collection and analysis, discussion of the results, preparation of the manuscript.

Olga V. Shevaldova – participation in the development of the research concept, data collection and analysis, discussion of the results, preparation of the manuscript.

Author Details

Alexander V. Vartanov – Cand. Sci. (Psychology), Senior Researcher, Lomonosov Moscow State University, Moscow, Russian Federation; ResearcherID: D-9907-2012, Scopus ID: 6603018783, Author ID: 72326, ORCID ID: <https://orcid.org/0000-0001-8844-9643>; e-mail: a_v_vartanov@mail.ru

Veronika M. Zubko – Laboratory Assistant, Department of Psychophysiology, Faculty of Psychology, Lomonosov Moscow State University, Moscow, Russian Federation; ORCID ID: <https://orcid.org/0009-0002-2513-8359>; e-mail: q158veronika@gmail.com

Vasilisa D. Abrosimova – Laboratory Assistant, Department of Psychophysiology, Faculty of Psychology, Lomonosov Moscow State University, Moscow, Russian Federation; ORCID ID: <https://orcid.org/0009-0009-9296-714X>; e-mail: vasilisaabr@yandex.ru

Mariia D. Krysko – Assistant Professor, Department of General Psychology, L.S. Vygotsky Institute of Psychology, Russian State University for the Humanities, Moscow, Russian Federation; ORCID ID: <https://orcid.org/0000-0001-9263-5203>; e-mail: mariya.krysko@mail.ru

Daria A. Leonovich – Graduate Student, Russian Presidential Academy of National Economy and Public Administration, Moscow, Russian Federation; ORCID ID: <https://orcid.org/0009-0001-3028-2278>; e-mail: dagubareva@gmail.com

Olga V. Shevaldova – Research Assistant, Federal Research Center for Innovative and Emerging Biomedical and Pharmaceutical Technologies, Moscow, Russian Federation; ORCID ID: <https://orcid.org/0000-0001-8577-4280>, Author ID: 9395-5102; e-mail: shevaldova_ov@academpharm.ru

Conflict of Interest Information

The authors have no conflicts of interest to declare.