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Stimulating neuroplasticity: Therapeutic applications of an extended digital musical instrument

Elena Partesotti [a,b*], Jamille Almeida Feitosa [b,c,d*], Jônatas Manzolli [a] and Gabriela Castellano [b,c]

[a]Interdisciplinary Nucleus of Sound Communication, UNICAMP, Campinas, Brazil; [b]Brazilian Institute of Neuroscience and Neurotechnology (BRAINN), Campinas, Brazil; [c]Gleb Wataghin Institute of Physics, University of Campinas (UNICAMP), Campinas, Brazil; [d]School of Applied Mathematics, Getulio Vargas Foundation (FGV), Rio de Janeiro, Brazil

ABSTRACT

Introduction: Music therapy has been widely applied to aid individuals both psychologically and physically, including as rehabilitation training for stroke patients. Recently, the use of novel technologies such as Digital Musical Instruments (DMIs) and Virtual Reality (VR) has become more common in this field. To broaden the application of music therapy with these technologies to neurological patients, it is important to understand their effects on the brain.

Method: The aim of this propositional study is to present a quantitative evaluation of brain network changes, using functional Magnetic Resonance Imaging (fMRI), occurring in individuals who used an XR-based Extended DMI (EDMI), namely, BehCreative. BehCreative is an immersive EDMI that provides sound and visual feedback based on the user's body movements. Five healthy individuals underwent ten training sessions with BehCreative and resting-state fMRI scans (before the first and after the last session).

Results: Functional connectivity changes between those scans were examined. A strengthened connection between brain areas associated with movement and audiovisual feedback processing was identified, possibly associated with an increase in motivation and cognitive engagement during audio-visual tasks. In general, connectivity changes pointed to an increase in arousal in the tested subjects, which may have been linked to the activation of the reward system during the use of the EDMI.

Discussion: These results are in line with our initial hypothesis, which was that training with BehCreative stimulates the neuroplasticity of the reward system. This study builds upon our previous research, on the therapeutic potential of DMIs.

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KEYWORDS DMI; music therapy; Creative Empowerment; fMRI; neuroplasticity; rehabilitation

Introduction

Music therapy has been recognized as an effective discipline for providing both psychological and physical aid to individuals. Reviews highlight its effectiveness in

CONTACT Elena Partesotti eparteso@unicamp.br

*These authors contributed equally to this work.

improving well-being and health outcomes across various populations. For instance, Bradt et al. (2021) show that music interventions can significantly reduce anxiety and depression, manage pain, and improve quality of life in cancer patients. Additionally, studies highlight the benefits of music therapy for individuals with schizophrenia and similar disorders, showing significant improvements in mental health and quality of life (Geretsegger et al., 2017).

This discipline has expanded to include post-stroke motor rehabilitation, showing significant benefits (Altenmüller et al., 2009; Thaut et al., 2007). Recent studies demonstrate that music therapy enhances motor function and cognitive recovery post-stroke. Magee et al. (2017) and Sihvonen et al. (2017) highlight the positive impact of music-based interventions in neurological rehabilitation, facilitating neuroplasticity, improving gait and movement, and enhancing cognitive function. Scholz et al. (2016) further support music therapy's role in neurorehabilitation, emphasizing its effectiveness in motor function and cognitive recovery.

In fact, music's profound impact on the brain, particularly in emotional modulation, underscores its therapeutic value (Koelsch, 2014, 2018). Music stimulates the nervous system and can alter brain structures in people who listen to it. In his review on the importance of music in the stimulation and evocation of emotions, Koelsch (2014) underlines the potential of music in modulating the activity of brain structures crucially involved in emotions, such as the amygdala, nucleus accumbens, hippocampus, insula, cingulate cortex, and orbitofrontal cortex. In another review, the author underlines how music can change physiological components such as arousal and relaxation (Koelsch, 2018). Furthermore, understanding which parts of the brain are stimulated by aesthetic emotions (Koelsch, 2018) also offers potential in music therapy. Indeed, some musical characteristics and experiences produce desired neural activation patterns implicated in emotion regulation (Moore, 2013).

Emotion regulation is characterized by increased activation in the cognitive control and monitoring areas – the anterior cingulate cortex, orbitofrontal cortex, and lateral prefrontal cortex – which leads to decreased activation in the amygdala (Moore, 2013). Previous studies using fMRI have shown that cognitive control can have an impact on the modulation of the connectivity of the cerebral network (Finc et al., 2020), while reward-related arousal mechanisms have been linked to music-induced emotions (Blood & Zatorre, 2001; Koelsch, 2015). The music-stimulated reward system can, at the same time, maximize pleasure and inhibit structures associated with negative emotions (Blood & Zatorre, 2001). Furthermore, the pathway for arousal and valence, when it comes to emotions, does not have a clear and precise division, but can go "hand in hand" so to speak: Arousal and relaxation can coexist, especially while listening to music (Koelsch, 2015).

Changes in emotional perception can influence cognitive control, ultimately affecting how individuals respond to conflict-driven virtual situations (Brühl et al., 2014; Inzlicht et al., 2015). Some of the areas that are included in cognitive control are the medial prefrontal and anterior cingulate cortices, and the insula. However, other studies have implicated other regions such as the dorsolateral prefrontal cortex (DLPFC), the parietal cortex, the striatum, and the cerebellum (Friedman & Robbins, 2021; Leisman et al., 2016). Increased activation in the cognitive control areas leads to motion regulation, and this suggests that the subject becomes aware of their movements striving to reach their precise goal, which in this context implies creating their own "path" for satisfying audio-visual feedback (Moore, 2013). Therefore, understanding how novel music technologies influence brain function necessitates a comprehensive approach that integrates qualitative observations from therapists with quantitative data from music and neuroimaging technologies, such as fMRI or electroencephalography.

While traditional instruments remain common in the daily practice of music therapy sessions, the integration of Digital Musical Instruments (DMIs) and Virtual Reality (VR) has grown (Partesotti, 2023). VR technology is emerging as a powerful tool in various fields of therapy, including music therapy. As a matter of fact, technologies within the neurotechnological field, such as DMIs and VR, have demonstrated great potential in music therapy (Corrêa et al., 2009). As described in a recent review (Feitosa et al., 2022), VR has already been applied to the neurofunctional rehabilitation of patients suffering from conditions such as post-stroke (Brandão et al., 2020; Mekbib et al., 2021; Rutkowski et al., 2020), multiple sclerosis (Maggio et al., 2019), Parkinson's disease (Dockx et al., 2016; Pazzaglia et al., 2020), and cerebral palsy (Ravi et al., 2017), among others.

Recent reviews by Koelsch (2014, 2018) provide comprehensive insights into the physiological and psychological mechanisms by which music therapy can influence mental health. These reviews underscore the necessity for innovative approaches, including VR, to enhance the efficacy of music therapy. Several studies have begun to explore the intersection of VR and music therapy. For instance, Bellinger et al. (2023) conducted a randomized controlled study on the application of VR exposure versus relaxation training in music performance anxiety, demonstrating significant potential in reducing anxiety levels. Similarly, Danso et al. (2022) reviewed the implications of VR in music therapy, particularly for patients with neglect, offering a narrative review that highlights the therapeutic benefits. Brungardt et al. (2021) piloted the use of VR-based music therapy in palliative care, showing promising results in improving patient well-being. Additionally, Tamplin et al. (2020) developed and tested an online VR platform for delivering therapeutic group singing interventions for people with spinal cord injury, indicating feasibility and positive outcomes. Earlier studies, such as Optale et al. (2010), have also shown that VR memory training can help control memory impairment in elderly adults, further supporting the integration of VR in therapeutic settings. XR (Extended Reality) is an umbrella term encompassing VR, Augmented Reality (AR), and Mixed Reality (MR), offering diverse opportunities for interactive and immersive experiences (Rauschnabel et al., 2022). Research indicates that XR can create immersive and controlled environments that enhance therapeutic outcomes. In the study reported here, we aimed to explore the integration of XR in order to examine the feasibility of this environment and highlight any potential benefits and applications in music therapy and rehabilitation.

This exploratory study, a follow-up to a prior one (Partesotti et al., 2018), explores the potential of Extended DMIs (EDMIs), proposing further insights into the effectiveness of these tools within music therapy and rehabilitation. We evaluated brain regions associated with the motor system, visual and auditory systems, reward system, and affective system. The main aim of this work is thus to present a quantitative evaluation of brain changes, using fMRI, occurring in individuals who used an XR-based EDMI, namely, BehCreative, developed by one of the authors.

Research purpose and aims

Given these considerations, this study explores the integration of EDMIs within the context of music therapy through a propositional pilot investigation, building upon prior research (Partesotti et al., 2018). The main aim of this work is thus to present a quantitative evaluation of brain changes, using fMRI, occurring in individuals who used an XR-based EDMI, namely, BehCreative, developed by one of the authors. BehCreative is an immersive EDMI that generates sound and visual feedback in response to the user's movements. This EDMI can be considered a musical training tool, which allows the user to play with their whole body. It presents no interface between the body and the production of music and this helps to overcome any physical and psychological problems the subject may have. It also enables the consideration of different musical characteristics – such as the use of dissonance and consonance controlled by the user and the use of music combined with visual stimuli – and thus it may become a potentially useful tool for emotion-regulation awareness. Visual processing software to communicate with Kinect 2, a motion-sensing device, was developed on the Windows platform, while Pure Data Extended was implemented on iOS, with patches designed to produce specific sounds in response to defined movements, known as Virtual Affordances (Partesotti et al., 2024a). Additionally, two other musical programs were used to create consonant and dissonant background sounds. Kinect 2 tracks participants' full-body movements to generate synchronized sound and visual feedback. This setup enables participants to interact with the musical environment without traditional physical interfaces, fostering a more immersive and intuitive experience. The Open Sound Control (OSC) protocol (Wright, 2002) was used so that the two platforms (Windows and iOS) could communicate in real time. All sounds were listened to through an octophonic loudspeaker system (Figure 1). The latency between the visual stimulus and the sound response to user movement was minimal, as the two processes were executed in parallel (sampling rate was 30 frames per second, which was the base rate of the Kinect 2 used in the experiments).

We hypothesize that training with BehCreative stimulates the neuroplasticity of the reward system and can be leveraged by the therapist both in music therapy and motor rehabilitation. We aim to offer reliable tools for data analyses that usually rely only on qualitative observation between the user and a traditional instrument during music therapy. We acknowledge that using fMRI is costly and complex to operate; therefore, our proposed method should be understood as complementary to existing methods. Considering that VR tools used for rehabilitation usually make use of pre-defined tasks and goals set for the user, and the goals' achievement activates the reward system (Saposnik, 2016), we propose an EDMI where goals are established by the subject during the sessions. This makes the subject a self-trainer, learning to self-regulate through movement and setting their own limits and goals, leading to a co-determination process of Creative Empowerment. This process aims to amplify participants' creativity and give them a sense of control and agency over the creative process (Partesotti et al., 2024a). It is also associated with enhanced sensory gating and attention control (Partesotti, 2023). Despite the potential of DMIs for therapeutic purposes, their use is not yet widespread, and examples are scarce (Peñalba et al., 2019). To the best of our knowledge, no studies have investigated brain changes resulting from the use of an XR-based EDMI using fMRI.

Hence, this study aims to investigate the effects of BehCreative on brain network changes using fMRI, focusing on how XR-based EDMI influences emotional regulation and enhances creative expression during music therapy sessions. Through this research, we hope to uncover new insights into the potential of XR-based DMIs to enhance emotional regulation and creativity, ultimately advancing the field of music therapy.

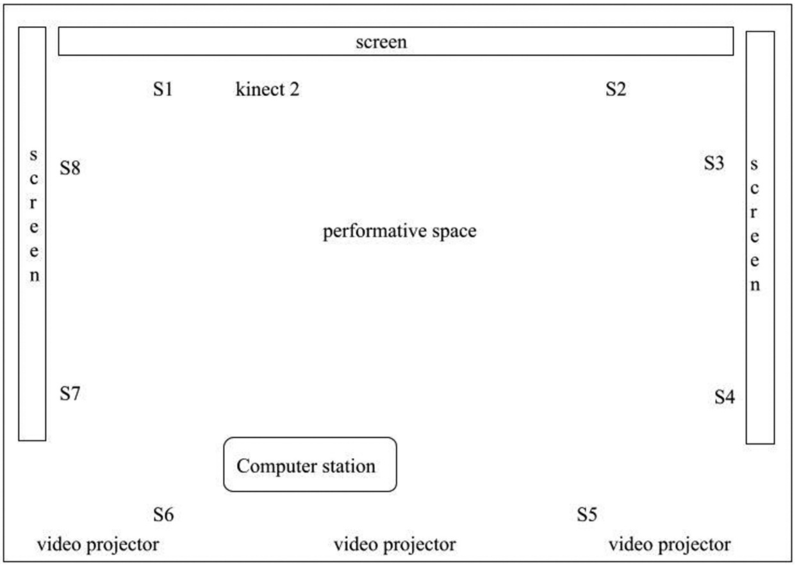

Figure 1. Architecture of BehCreative. The user moves in the center of the studio with three large screens in front and on both sides providing the visual feedback. The setup includes an octophonic sound system with eight speakers (S1–S8) placed around the user. A Kinect2 tracks upper-limb gestures, which control the audiovisual feedback. The visuals on the screens change in response to the user's movements, varying in shape, colour, and brightness. For further details, see Partesotti, 2023 and Partesotti et al., 2024b.

Methods

Recruitment of participants

This research design utilized an exploratory, non-randomized group design. We employed pre/post-session comparisons of behavioural self-reported data, alongside fMRI data collected at two key points: before the first session and following the final session.

Participants were recruited through internal email invitations sent to various university departments, including arts, dance, music, physical education, and others. Recruitment targeted individuals who met the study's inclusion criteria, which included being healthy, having musical knowledge, conducting regular physical activities like dancing, or having no musical knowledge or dance experience. Initially, ten participants of different ages were recruited for this study (age 21–38 years; five women) from a university environment. These participants were healthy individuals with no history of neurological diseases and provided written informed consent. While we recorded basic demographic information such as age and gender, detailed information on prior experience with virtual reality, handedness, other diseases or psychiatric conditions, medication, and substance use (including coffee, alcohol, and tobacco) was not collected. Similarly, data on sleep patterns and involvement in specific sports or specific physical activities were not obtained.

Participants had to attend 10 training sessions (one session a day for two weeks, Monday to Friday) with BehCreative, and undergo two resting state fMRI scans: one before the first training session and one after the last (10th) session. However, some participants had their training protocol interrupted due to Covid-19, and none completed their final fMRI scan. The five remaining participants attended ten sessions and both fMRI exams each. The scans of these five participants (age 25–38 years, three women) were screened for changes in this article.

Ethical considerations

Approval for human participants' research was obtained by the Ethics Committee of the University of Campinas – protocol 79,851,317.40000.5404 – and informed consent was obtained from study participants.

All participants provided written informed consent prior to enrolment in the fMRI experiment. The consent form included details about the study purpose, MRI procedures, potential risks associated with MRI scanning (e.g. noise, confined space), as well as the risks and benefits of participation, and participant rights. Participants were informed that participation was voluntary and they could withdraw at any time without penalty. The consent form was in Portuguese. Participants were given ample time to review the consent form, ask questions about the MRI procedures, and discuss any concerns with the research team before signing. A copy of the signed consent form was offered to each participant for their records. Participants were also screened for MRI safety and eligibility prior to the scanning session.

Description of the setting and procedures

Participants underwent ten training sessions over two weeks (Monday to Friday), each lasting 30 minutes, using BehCreative EDMI. The resting state fMRI scans were performed before the first and after the last training session. Participants were instructed they could move freely within the performative space, with their body movements tracked by Kinect 2 to interact with the XR environment. The sound, delivered through an octophonic loudspeaker system, was set at a comfortable listening level (less than half the maximum, considering the soundproofed and immersive environment) and participants were not allowed to change the volume in order to maintain consistency across sessions and participants. We ensured that the volume was safe and non-intrusive.

Protocol design

In this pilot study, we analyzed the responses of five participants with varied skills and backgrounds. Of these participants, one had prior experience in musical activities, two had experience in dance, and two had no prior experience in either music or physical activities. The study evaluated participants' reactions to audio-visual stimuli, examining their learning capacities as well as their emotional and improvisational feedback after free movements and exploration. The sessions were divided into two parts. In the first part, the Exploration Phase, participants had three minutes to freely explore the space with their bodies, without any specific instructions. They were encouraged to move around and interact with the environment naturally. Following this, the Improvisation Phase allowed participants up to five minutes for free improvisation, during which they could stop at any time. In this phase, participants were free to experiment with their movements to produce various audiovisual effects. The environment was designed to be immersive, featuring a dark, soundproof room.

Participants were surrounded by three screens displaying images linked to the sounds generated by their movements. An octophonic sound system provided audio feedback, enhancing the multimodal experience (Figure 1). Moreover, the latency between the visual stimulus and the sound response to user movement was minimal, as aforementioned.

Data collection: Behavioural data

Questionnaires based on the Affective Slider model (Betella & Verschure, 2016) were administered before and after the experiment to evaluate changes at the behavioural level. These self-assessment questionnaires provided data on the participants' emotional states and learning experiences. Although the detailed analysis of these questionnaires is covered in another article (Partesotti et al., 2024b), their use indicates that behavioural data were indeed collected and are available for further interpretation of the neuroimaging data. In this paper, we focus on the analysis of fMRI data.

Regarding the physiological measurements such as heart rate, galvanic skin response, or other parameters related to arousal, these were not collected during the training sessions. The primary objective of our study was to explore the neural mechanisms underlying the use of the XR-based EDMI, BehCreative, and its impact on neuroplasticity, which is best captured through fMRI analysis. While physiological measures can indeed provide valuable insights into arousal and emotional states, the focus on fMRI allowed us to obtain high-resolution images of brain activity and connectivity changes specifically related to the reward system and cognitive control areas. Collecting physiological data such as heart rate or galvanic skin response would have required additional tests before and after the experiment, significantly increasing session time and potentially interfering with fMRI scan outcomes. Therefore, we decided to omit these measures.

Data collection: fMRI and BehCreative data

For this study, we collected both neuroimaging and movement-based data to analyze participants' cognitive and emotional engagement.

fMRI data acquisition and preprocessing

Resting state fMRI data were acquired for each subject on two occasions: before the first training session and after the last. These scans were performed on the same days as the experiments. Participants were instructed to lie down comfortably inside the MRI scanner and to remain as still as possible throughout the scanning process to prevent motion artifacts. They were asked to maintain a calm and restful state, avoiding focused thoughts. Participants were informed about the loud noises produced by the MRI machine and were provided with earplugs to minimize discomfort from the noise. The MRI protocol consisted of a T1 – weighted anatomical image (isotropic voxel of 1 mm^3, FOV = $240 \times 240 \times 180$ mm^3, repetition time (TR) = 7 ms, echo time (TE) = 3.2 ms) and T2* – weighted functional images (voxel size = $3 \times 3 \times 3$ mm^3, no gap, FOV = $240 \times 240 \times 117$ mm^3, TR = 2 s, TE = 30 ms, flip angle = 90, 180 volumes), acquired in a 3.0 Tesla scanner (Achieva 5.3.1, Philips Medical Systems, The Netherlands).

The images were manually reoriented to the anterior commissure in the SPM12 toolbox. The next steps were performed in the UF2C software (de Campos et al., 2020). The functional images were movement corrected and coregistered to the structural image. The structural image was segmented into white matter, grey matter and cerebral spinal fluid, and both structural and functional images were normalized to the MNI template. A spatial Gaussian filter and a temporal bandpass filter (0.08–0.1 hz) were applied to the functional images.

The brain was parcellated using 52 regions of interest (ROIs) from the AAL3 atlas (Rolls et al., 2020). The ROIs chosen included the limbic system, dopaminergic pathways and regions associated with motor function (Table 1). Each ROI had its time series extracted and used to build weighted functional connectivity (FC) matrices (van den Heuvel & Hulshoff Pol, 2010). These matrices were generated for each subject using Pearson correlation, computed for each pair of ROIs. Negative correlation values were discarded.

BehCreative data

BehCreative stands for Behave Creatively and is an immersive EDMI, with the aim of deepening the user's creativity behaviour. To do this, BehCreative has been set up with sound characteristics such as consonance and dissonance, which precisely represent the tensions that stimulate the affective reaction (Koelsch, 2013) of the subject.

Throughout the history of music, various concepts of dissonance have been proposed, often linked to techniques and styles of harmony and counterpoint (da Silva & Faria, 2018; Tenney, 1988). In the twentieth century, Hermann von Helmholtz's work laid the foundation for studying dissonance based on its psychoacoustic properties, known as sensory dissonance (von Helmholtz,

Table 1. List of ROIs and labels used in this work, obtained from AAL3

Anatomic/functional description	Labels	Regions of Interest (ROIs)
Temporal lobe and dopamine pathways	R/LFd	(Right/Left) Dorsolateral prefrontal cortex
	R/LFiop	(Right/Left) Inferior opercullum
	R/LFob	(Right/Left) Prefrontal orbital cortex
	R/LACC	(Right/Left) Anterior cingulate cortex
	R/LAUD	(Right/Left) Auditory cortex
	R/LITG	(Right/Left) Inferior temporal gyrus
	R/LHIP	(Right/Left) Hippocampus
	R/LAMY	(Right/Left) Amygdala
	R/LINS	(Right/Left) Insula
	R/LPAL	(Right/Left) Pallidum
	R/LNAC	(Right/Left) Nucleus accumbens
	R/LSN_VTA	(Right/Left) Substantia nigra & ventro tegmental area
Motor related regions	R/LS1	(Right/Left) Primary somatosensory cortex
	R/LS2	(Right/Left) Secondary somatosensory cortex
	R/LM1	(Right/Left) Primary motor cortex
	R/LSMA	(Right/Left) Supplementary motor area
	R/LdSTR	(Right/Left) Dorsal striatum
	R/LTHA	(Right/Left) Thalamus
	R/LCER3	(Right/Left) Cerebellum III
	R/LCER45	(Right/Left) Cerebellum IV & V
	R/LCER6	(Right/Left) Cerebellum VI
	R/LCER8	(Right/Left) Cerebellum VIII
	R/LCER9	(Right/Left) Cerebellum IX
	R/LCERCI	(Right/Left) Cerebellum crus I
	R/LCERCII	(Right/Left) Cerebellum crus II

1954). This concept isolates dissonance based on the physical properties of sound and the physiological properties of the human ear (Terhardt, 1984). Sensory consonance, in turn, describes how pleasant sounds are perceived by listeners, anchored in roughness, sharpness, and tonalness (Terhardt, 1984). Roughness, particularly significant in music, has been used in sound synthesis models and multimodal perception studies. The roughness model, based on Zwicker's critical band concept, calculates roughness in complex sounds by considering the physical properties of amplitude modulation and the characteristics of critical bands (Plomp & Levelt, 1965; Vassilakis, 2001; Zwicker et al., 1957). Using psychoacoustic metrics, sensory dissonance becomes a measurable attribute through mathematical models, allowing for a comprehensive analysis beyond traditional musical practices of harmony and counterpoint.

Particular attention was given to the audio-visual correspondence: Consonant sounds are linked to the colours of the visual feedback, while white and grey gradations are linked to the dissonance that occurs when the subject slows down their movements without continuity in acceleration. The point of rest – paramount when referring to music therapy sessions (Partesotti et al., 2018) – occurs when the subject stops, so no feedback is displayed or listened to.

fMRI analysis

The connectivity difference between the two fMRI scans was calculated for each subject by subtracting the pre and post adjacency matrices (post–pre). The group adjacency matrix was computed as the median of all participants' difference matrices. The median was chosen given the small size of the population, because it is less influenced by outliers and therefore seemed more representative than the mean. The group matrix was submitted to a z-test with a significance level $\alpha = 0.001$ to detect significant changes.

Strength variations across the temporal lobe and dopamine pathways

To further explore brain changes associated to the reward, visual and auditory processing systems, the strength parameter (from graph theory, see e.g. Rubinov & Sporns, 2010) was investigated in the ROIs belonging to the temporal lobe and dopamine pathways (see Table 1).

From a graph theory stand-point, the parcellated brain can be seen as a network in which the ROIs are the nodes and their relations (represented by the connectivity matrices) are the links (Rubinov & Sporns, 2010). The strength (S) is a parameter that measures how strongly connected a given node is. The strength of a node i is given by:

$$S_i = \sum_{j=1}^{n} w_{ij} \tag{1}$$

where w_{ij} are the weights of the connections made by this node.

The relative strength variation was computed for each subject (over positive correlations) as:

$$\Delta S = (S_{pos} - S_{pre})/S_{pre} \tag{2}$$

The median over the participants was taken as the group's result. Again, the median was chosen over the mean due to the small population size.

This analysis was applied to the ROIs involved in the perception of the audio-visual stimuli (R/LAUD and R/LITG), to the limbic system (R/LHIP, R/LAMY, R/LINS, R/LNAC, R/LPAL and R/LSN_VTA) and regions in the frontal lobe associated to the mesocortical pathway (R/LFd, R/LFob and R/Liop).

Results

Figure 2 shows a representation of the difference connectivity matrix for the group. The lower triangular part shows the group median variations in Pearson correlation (converted to z-score) between each pair of ROIs. The symmetric upper triangular part shows only the significant median variations (z-test, $p < 0.001$).

Between the baseline and the end of the training, five connectivity increases and six decreases were found. Four positive variations occurred in the right hemisphere and the other one in the left hemisphere. Four negative variations occurred in the left hemisphere, and two were interhemispheric.

Table 2 presents the relative variations in the strength parameter for the subnetwork composed of the temporal lobe and dopamine pathways regions. Absolute values ranging from 10% to 25% are shaded in light grey, while values exceeding 25% are shaded in dark grey.

Discussion

In this study, we aimed to quantify brain network changes using resting-state fMRI, possibly resulting from training with a XR-based EMDI. Since the subject is learning to play an EDMI, the rationale behind our hypothesis is that audio-visual feedback affects the subject's motor and affective learning. Participants would need to reach a certain skill level to build their sensorimotor maps to play

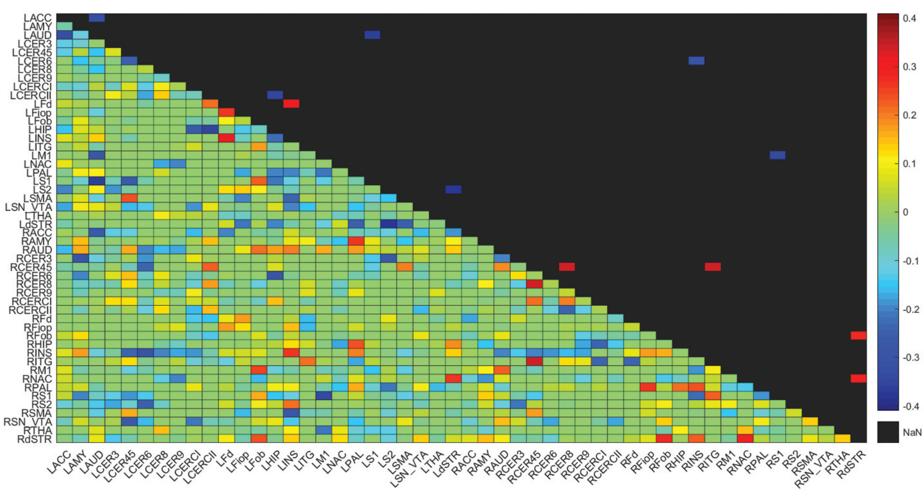

Figure 2. Group difference connectivity matrix between before and after training with BehCreative

Table 2. Strength relative variations within the temporal lobe and dopamine pathways subnetwork

Strength relative variations			
Left hemisphere	%ΔS	Right hemisphere	%ΔS
LITG	35	RITG	41
LAUD	−3	RAUD	5
LFd	30	RFd	8
LFiop	−8	RFiop	25
LFob	14	RFob	−1
LACC	−21	RACC	−17
LAMY	19	RAMY	28
LHIP	−6	RHIP	23
LINS	16	RINS	15
LNAC	−4	RNAC	17
LPAL	−24	RPAR	1
LSN_VTA	−7	RSN_VTA	0

Absolute values from 10% to 25% are shaded in light grey and values above 25% are shaded in dark grey.

the EDMI with their body, with their movements activated by visual or consonance/dissonance feedback. In the analysis, we identified several variations in brain activity associated with neuroplasticity. Among these, an increase in motivation and cognitive engagement during audio-visual tasks and a strengthened connection between brain areas associated with movement and audio-visual feedback processing were identified. An increased connection between the dorsolateral prefrontal cortex and the insula, possibly related to pleasure activation, arousal, and cognitive processes, was also found. Also, a decrease in brain activity was observed in areas associated with motor control, memory formation, emotional and sensory processing. Additionally, an increase in activity was discovered in brain areas related to visual stimulus processing, executive control, attentional control, decision-making, memory, and emotional responses, which may be related to the exploratory behavior of EDMI participants.

Positive variations

Positive variations were found in connections between the dorsal striatum and both the nucleus accumbens and the orbitofrontal cortex (RdSTR–RNAC and RdSTR–RFob). The orbitofrontal cortex, involved in sensory integration and reward-based decision-making (Kringelbach, 2005; Padoa-Schioppa et al., 2011), works with the basal ganglia (including the nucleus accumbens and dorsal striatum) through corticostriatal pathways to translate motivation into goal-directed behavior (Balleine et al., 2007; Haber, 2016; Kringelbach & Rolls, 2004). The nucleus accumbens interfaces between the limbic and motor systems, playing a significant role in outcome evaluation and reinforcement learning (Mogenson et al., 1980). The dorsal striatum is involved in action selection and movement initiation (Balleine et al., 2007; Kwak & Jung, 2019). The strengthened connections likely reflect the movement-related reward nature of the audio-visual feedback provided by the system. These connections are associated with increased motivation and cognitive engagement during exploration with the EDMI, as well as with body awareness, motor control, and emotional processing. This suggests that the system effectively engages multiple brain regions, enhancing the user's experience.

Another increased connection was between the dorsolateral prefrontal cortex and the insula (LFd–LINS). The insula is involved in sensory interoceptive representations, motor control, audio-visual integration, auditory perception, and emotional processes (Koelsch, 2014, 2015). The increase in this connection might be due to pleasure activation, arousal, and cognitive processes. The anterior-prefrontal cortex is responsible for strategic processes in memory recall and cognitive control of behavior that facilitate goal attainment. An increase in this connection corresponds to an increase in arousal (Koelsch et al., 2015). Emotional arousal is related to the reward aspects of music listening (Salimpoor et al., 2009), and this reward-related increase in arousal may also occur during the process of creating music and exploring BehCreative. Given the small sample size in our study, this finding should be considered with caution.

Increased connections were also observed between the cerebellum and inferior temporal gyrus (RCER45–RITG), and intracerebellar regions (RCER45–RCER8). The inferior temporal gyrus processes visual stimuli, tone, and pitch (Nozaradan et al., 2017). The cerebellum plays roles in sensorimotor, cognitive, and affective tasks (Peterburs & Desmond, 2016; Stoodley et al., 2012), including rhythmic synchronization (Molinari et al., 2007). This increase may indicate physical movement following timing and rhythm while processing tone and visual feedback during interaction. The intracerebellar increased connection involved regions associated with sensorimotor functions (Stoodley & Schmahmann, 2018), facilitating motor learning and movement coordination (Olszewska et al., 2021).

Negative variations

Negative variations occurred in connections between the cerebellum and both the hippocampus and insula (LCERCII–LHIP, LCER6–RINS), the auditory cortex and both the anterior cingulate and primary somatosensory cortex (LAUD–LACC and LAUD–LS1), the dorsal striatum and secondary somatosensory cortex (LdSTR–LS2), and the primary motor and primary somatosensory cortices (LM1–RS1). These areas are associated with motor control, memory formation, emotional processing, sensory information processing, and motor planning. Decreased connectivity in these regions may suggest reduced sensory and motor processing during the task. A decrease in activity in these latter areas may suggest a decrease in sensory processing during the task. Bravo et al. (2020) found increased functional connectivity between the LAUD and the LACC as an effect of dissonant sounds in comparison to consonant sounds. This result was interpreted as a greater need for information integration to deal with the conflicting emotions produced by the dissonant sounds (Bravo et al., 2020) during the performative action. LdSTR and LS2 are associated with the processing of sensory information, while LM1 and RS1 are involved in motor planning and execution. A decrease in connectivity between these regions may indicate a decrease in sensory and motor processing during a task, which could have various implications depending on the specific task and context. Considering the audio-visual stimuli proposed in our tasks, a negative connectivity variation in these regions could suggest a decrease in the integration of visual and auditory information, which may impact the perception and interpretation of the stimuli.

Regarding graph parameter strength, significant variations (>25%) were found in the inferior temporal lobes (LITG and RITG), LFd, RFiop, the frontal lobe, and amygdala (RAMY). These regions are involved in visual stimulus processing

(Conway, 2018), executive function control (Friedman & Robbins, 2021; Nejati et al., 2021), attentional control (Hampshire et al., 2009), decision-making, memory, and emotional responses (Šimić et al., 2021). This suggests highly explorative behavior of the participants, linked to the nature of the EDMI, where auditory and visual stimuli are closely related. Increased activity in the RAMY indicates the audio-visual stimuli had an emotional component, influencing memory formation and emotional processing.

Strength variations between 10% to 25% were found in the LFob, LAMY, RHIP, L/RINS, and RNAC. These regions are involved in reward evaluation, reward-based decision-making, reinforcement learning, movement initiation, spatial navigation, memory, and emotional processes. Variations in these regions reflect differences in emotional, cognitive, and reward-related processes.

The hippocampus is associated with spatial navigation and memory (Goodroe et al., 2018, Nadel, 2008), the insula is associated with interoceptive representations, audio-visual integration, auditory perception and emotional processes and the decision to initiate/continue the movement (Koelsch, 2015; Protas, 2018). Therefore, variations in these regions could reflect differences in emotional, cognitive, and reward-related processes, depending on the specific performance completed by the volunteer.

Negative strength variations between 17% and 24% were observed in the anterior cingulate cortex (both hemispheres) and LPAL. The ACC is involved in emotional recall (Phan et al., 2004), with decreased activity possibly indicating reduced perceived pain (DeCharms et al., 2005). The ventral pallidum processes both reward and aversive stimuli, with functional connectivity changes depending on task conditions (Steel et al., 2019).

Interestingly, regions associated with the limbic system (hippocampus, amygdala, insula, and nucleus accumbens) showed greater variations in the right hemisphere, aligning with studies on brain asymmetry in emotion, spatial and visual information processing, and music recognition (Rotenberg & Weinberg, 1999).

Conclusion

We presented here a quantitative fMRI data analysis of brain network changes possibly associated with training with a XR-based EMDI tool, namely, BehCreative. To the best of our knowledge, this is the only work that has evaluated an EMDI for music therapy from the point of view of its neural effects.

The obtained results showed a reward-related increase of arousal in the tested participants, which is probably linked to the sense of reward/Creative Empowerment during the use of BehCreative, in particular during the process of creating music and exploration of the tool. This, in turn, is possibly due to an increase in motivation, pleasure activation and cognitive engagement. These results are in line with our initial hypothesis, which was that training with BehCreative stimulates the neuroplasticity of the reward system, and can be exploited by the therapist both in music therapy and motor rehabilitation. This exploratory study was performed on healthy people, but the next step will be to apply BehCreative to people with disabilities.

In conclusion the findings suggest that training with BehCreative, an XR-based EDMI, induces changes in brain connectivity and network parameters, reflecting the movement-related reward nature of the audio-visual feedback provided by the system. Future research should address the study's limitations and include physiological measurements to validate these findings further.

Limitations and recommendations

This study has limitations, including a low number of participants, making it difficult to generalize the results. The COVID-19 pandemic interrupted data acquisition, limiting the sample size. Additionally, future studies should incorporate specific user goals within BehCreative, similar to other VR rehabilitation software, to minimize varied brain responses and improve consistency in the results. Future studies should also include larger samples and control groups performing similar tasks without the software to better attribute changes to BehCreative training. Moreover, implementing a longitudinal study to observe changes over time would help better understand the long-term effects of using EDMIs in music therapy. Including a more diverse participant pool is also essential to explore the effects across different demographics and clinical populations. Examining the impact of different environmental settings and conditions on the effectiveness of EDMIs could further enhance the understanding of how these factors influence outcomes.

Physiological parameters such as heart rate, galvanic skin response, or other arousal-related measures were not collected but can be used for validating the findings. Future research should incorporate these measurements. Finally, a detailed description of statistical methods used for multiple testing corrections can ensure robustness to the study. This includes specifying the type of correction method (e.g. Bonferroni correction, False Discovery Rate) and its rationale.

Disclosure statement

Elena Partesotti is Co-Guest Editor of this Special Issue of the Nordic Journal of Music Therapy. To avoid conflict of interest, Elena Partesotti was fully masked to the editorial process including peer review and editorial decisions and had no access to records of this manuscript. No other potential conflict of interest was reported by the authors.

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Notes on contributors

Elena Partesotti is a Postdoctoral Researcher at Unicamp, Brazil, working with the Interdisciplinary Nucleus for Sound Studies (NICS) and the Brazilian Institute for Neuroscience and Neurotechnology (BRAINN). Her interdisciplinary expertise encompasses musicology, cognitive science, neurotechnology, human-computer interaction, and music therapy, with a focus on connections to artistic installations and dance networks. Dr. Partesotti holds an International Doctorate Cum Laude in Musicology from the University of Valladolid, Spain, and Unicamp, Brazil. As a trained music therapist, she has applied her knowledge across diverse therapeutic and academic settings. During her doctoral research, she patented the EDMI e-mocomu, highlighting her contributions to the field. She also chaired the international conference ArtsIT 2023 and currently serves as Associate Editor of the International Journal of Art Therapy.

Jamille Feitosa holds a Bachelor's and Master's degree in Physics from the State University of Santa Cruz (UESC) and a Doctor of Science degree from the State University of Campinas (UNICAMP). She is currently a postdoctoral fellow in Machine Learning at Fundação Getúlio Vargas (EMAP - FGV).

Jônatas Manzolli fosters interdisciplinary dialogue between Science and the Arts, focusing on Music Composition, Computer-Aided Music Analysis, and Human-Computer Interaction in Artistic Domains. As a Full Professor at Unicamp's Institute of Arts, Brazil, he has led research at the Interdisciplinary Nucleus for Sound Studies (NICS/Unicamp) for 25 years. Collaborating globally with renowned research centers such as Neuroinformatics at ETHZ, SPECS Lab at UPF, and CIRMMT at McGill University, he has created works like "Ada: Intelligent Space" (2002) and "Re(PER)curso" (2007), exhibited at venues like the Barcelona Museum of Contemporary Art (MacBa). His musical compositions include three operas, including "Descobertas" and "Pássaros de Papel," awarded by the Rockefeller Foundation. Currently, he collaborates with Coimbra University's Department of Informatics Engineering and INET-md at the University of Aveiro, Portugal.

Gabriela Castellano is a Bachelor and Master in Physics from University of São Paulo and PhD in Electrical Engineering from King's College London. She worked at Eldorado Research Institute as a software engineer, and later held a post-doctoral position at Universidade Estadual de Campinas (UNICAMP), working with brain MRI processing. She is now Associate Professor and outreach projects coordinator at the Gleb Wataghin Institute of Physics at UNICAMP, head of the Neurophysics Group at UNICAMP, co-PI of project BRAINN (Brazilian Institute of Neuroscience and Neurotechnology, financed by FAPESP-Brazil), and coordinator (PI) of project DReANNs (Rehabilitation and Assistance Devices in Neuroscience and Neurotechnology, financed by FINEPBrazil). Her main research interests include the development and evaluation of assistive and rehabilitation technologies using functional connectivity derived from EEG and/or fMRI, braincomputer interfaces, and finding biomarkers from signals and/or images to aid diagnostic, prognostic and treatment of various neurological conditions.

ORCID

Elena Partesotti http://orcid.org/0000-0002-2878-3524

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