Transcranial magnetic stimulation of the right temporoparietal junction and left angular gyrus does not alter sense of joint agency in musical rhythmic coordination task: A pilot study

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Abstract

The sense of agency (SoA) refers to the perception that one's actions are influential and that one assumes responsibility for their consequences. In coordinated joint actions, a sense of joint agency emerges, with interaction and cooperation being crucial for enhancing SoA. Prior research indicates that the right temporoparietal junction (rTPJ) is integral to monitoring social contexts of SoA, while the left angular gyrus (lAG) focuses on individual aspects of agency. This study examined the effects of repetitive transcranial magnetic stimulation (rTMS) on SoA and judgment of performance (JoP) in eighteen healthy young participants using a three-way crossover design that included inhibitory neurostimulation of the rTPJ, excitatory stimulation of the lAG, and a sham intervention on the Vertex. Participants completed musical tasks involving rhythmic coordination before and after neurostimulation, with self-reported scores for SoA and JoP collected via Likert scales, alongside performance metrics (action time error and number of errors) evaluated through software. While rTMS did not yield significant effects on SoA, JoP, or performance overall, notable correlations between these variables suggest that neurostimulation may influence the interrelations among them. These findings highlight the complexities of how neurostimulation impacts perceived agency and performance, warranting further exploration into their interconnected dynamics.

Keywords: transcranial magnetic stimulation, right temporoparietal junction, left angular gyrus, sense of joint agency, musical rhythmic coordination, joint action

Introduction

A healthy person's brain typically uses the sensorimotor system to monitor and analyze changes in the body and environment after intending, planning, and carrying out an action (Haggard & Chambon, 2012). This process suggests a causal relationship, leading to a feeling or judgment—either implicit or explicit— commonly referred to as a sense of agency (SoA) (Frith, 2012; Moore & Obhi, 2012). SoA fosters a feeling of personal responsibility, control, and influence over the changes that occur. In other words, SoA refers to the personal experience of performing voluntary actions and observing their effects on the environment (Gallagher, 2000; Moretto et al., 2011; Frith, 2014; Haggard, 2017) (cf., Figure 1):

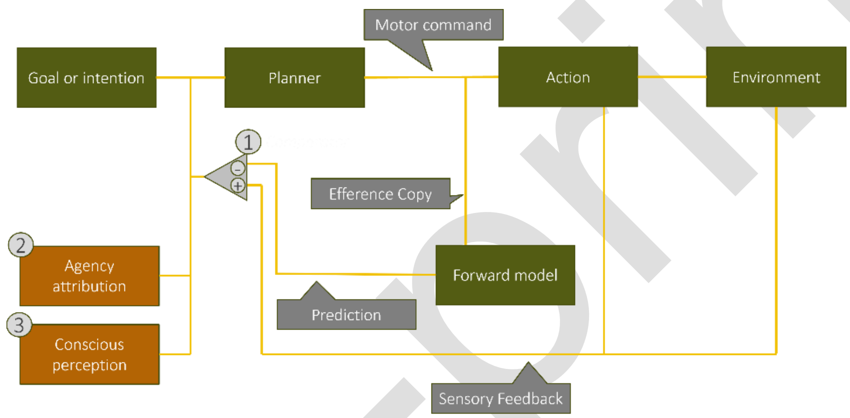

Figure 1. Comparator model for neural control of action and agency (Haggard, 2017)

SoA is a broad continuum that spans from an individual to a social context, and from a clear to vague SoA, influenced by various individual, social, and environmental factors (Silver et al., 2021). According to assumptions and findings from earlier studies, individuals experience a sense of personal agency when they carry out an action alone. Conversely, when people coordinate their actions, they may experience a sense of joint agency, as in "we did it together" (Pacherie, 2012).

It is likely that when people coordinate their actions, they perceive themselves as part of a cohesive unit, and the shared knowledge that develops in this context fosters a sense of joint agency (Dewey et al., 2012; Gallotti & Frith, 2013). Therefore, one of the key factors influencing the quality of the sense of joint agency is the nature and extent of social interaction and cooperation among individuals in a social context, such as during joint action (Silver et al., 2021). In the context of continuum model of SoA, several factors shape qualities of SoA such as temporal proximity between action and outcome (predictability of effect), freedom of choice in action, monitoring and inference of causality (the cause-and-effect relationship between action and outcome), and social context (Silver et al., 2021). The specialized brain regions related to the individual and social context of SoA in both individual and joint actions have been partially identified through various imaging, recording, and neurostimulation techniques.

According to previous studies (Sebanz et al., 2006; Pacherie, 2012), joint action is defined as any type of social interaction in which individuals coordinate their intention, goals, plans, and actions with one another at a common time or place in anticipation of changes in the environment. This ultimately results in a sense of joint agency and the sharing of responsibility (Beyer et al., 2017).

In this research we targeted two brain regions that are crucial in the emergence of a sense of joint and individual agency, respectively: right temporoparietal junction (rTPJ) (Ahmad et al., 2021; Schurz et al., 2017) and left angular gyrus (lAG) (Beyer et al., 2018) (cf., Figure 2). The rTPJ plays a key role in social cognition, particularly in monitoring social context and theory of mind activities, which are essential for understanding others' intentions and actions (Schurz et al., 2017). This makes rTPJ significant for SoA, especially in social contexts where joint action is involved. Joint action, a social skill, requires the ability to attend to, observe, share and coordinate actions with others closely linking it to theory of mind (Humphreys & Bedford, 2011). Given these functions, the rTPJ is implicated in various qualities of agency, particularly its social aspects. In contrast, the lAG primarily involved in the cognitive monitoring of SoA. It plays a crucial role in the general emergence of this sense but does not seem to be sensitive to the social context or its monitoring (Beyer et al., 2018). This suggests that while the rTPJ is more engaged in the social dimensions of agency, the lAG is more concerned with the individual's internal SoA, regardless of social context.

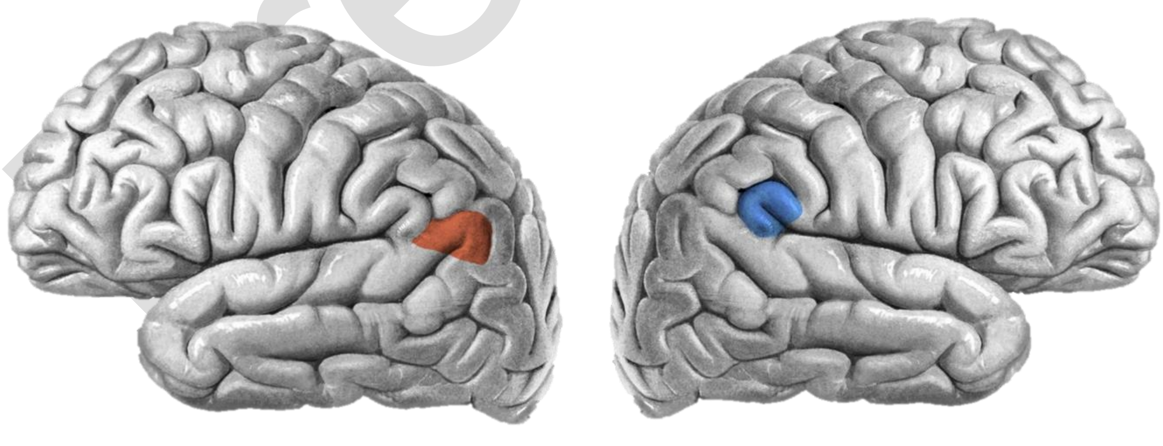

Figure 2. Right: Right temporoparietal junction (rTPJ); Left: left angular gyrus (lAG) (Case courtesy of Frank Gaillard, Radiopaedia.org, rID: 46670)

In a social context, the rTPJ naturally becomes more active, reflecting its sensitivity to external factors influencing an action. This increased activity in the rTPJ is crucial for processes related to theory of mind, such as attention orientation and understanding others' perspective (Lieberman, 2007; Schurz et al., 2014; Beyer et al., 2018). The rTPJ's role in these processes underscores its importance in monitoring and adapting to the social context, making it integral to the social aspects of SoA. Conversely, the lAG exhibits a negative correlation with the development of SoA. Increased activity in this region is associated with a reduced SoA, meaning that when lAG activity is high, individuals are less likely to feel in control or responsible for the outcomes of their actions. This is particularly evident when there is a discrepancy between the expected effects of an action and the actual outcomes, indicating that the lAG is sensitive to inconsistencies that disrupt the inference of causality (Chambon et al., 2013; Beyer et al., 2018). The lAG's role in this context highlights its involvement in monitoring and evaluating the consistency and predictability of actions, which is crucial for the formation of a coherent SoA.

Recent studies have shown that the anterior and posterior clusters of the rTPJ are involved in various cognitive functions. The anterior-posterior functional differentiation of this area has been reported by several studies, all of which confirm that the anterior and posterior clusters of this area are related to the control areas of attention and beliefs, respectively (D Decety & Lamm, 2007; Mitchell, 2008; Mars et al., 2012; Carter & Huettel, 2013; Krall et al., 2016).

The anterior cluster of the rTPJ may not be related to a simple bottom-up visual attention process, but rather directs the social attention process toward the joint action partner's behavior. This cluster may function as part of a system whose function is to shift or orient between internal-bodily state or self-perspective; and external-peripheral status or other-perspective (Corbetta et al., 2008). This attention-shifting function may also be related to the self-other distinction (Blakemore & Frith, 2003; Newman-Norlund et al., 2008) as well as detecting mismatches in our expectations of the actual outcomes of interactions with a partner (Corbetta et al., 2008; Koster-Hale and Saxe, 2013). Therefore, it seems that the rTPJa is more related to the recognition of the joint action partner's performance than to the individual's own performance (Abe et al., 2019). Therefore, our target neural area in all this study and neurostimulations is the anterior cluster of the rTPJ.

The complexity of monitoring behavior and the environmental interactions in social context, such as joint action, recruits multiple brain regions and nervous system interactions (Silver et al., 2021). While substantial research has focused on the low-level sensorimotor systems responsible for functions like observation, imitation, and action coordination in individual practices, fewer studies have examined the role of regions linked to high-level cognitive systems, particularly in joint actions. Imaging tools and neural activity recording can only provide evidence of correlation, not explaining their causal mechanisms (Kubit and Jack, 2013; Woods et al., 2016). Neurostimulation tools, like transcranial magnetic stimulation (TMS), overcome this limitation by allowing researchers to manipulate neural activity and observe the resulting effects, offering clearer insights into causality (Donaldson et al., 2015; Bardi et al., 2017). However, there remains a scarcity of studies that have employed such tools to investigate the causal relationships between neural activities and SoA within social contexts, particularly in scenarios involving joint action. This gap in research highlights the need for more focused studies using neurostimulation techniques to better understand the underlying mechanisms of joint agency. Therefore, in this study we employed TMS to explore whether applied repetitive TMS on rTPJ and lAG areas will enhance sense of joint agency during rhythmic coordination.

Given that social context and the presence of others influence individual performance (Gibson, 2014), it is essential to investigate how inhibitory neurostimulation targeting the rTPJ impacts performance in joint action scenarios. Further, while the sense of individual agency is required for intention, planning, and action at the individual level, as well as observation, imitation, and coordination at the social level (Crivelli, 2010, 2016; Crivelli and Balconi, 2015), it remains to be seen whether excitation the lAG improves individual performance in joint actions. Previous research has established that individuals' SoA is affected by their efficiency and performance in social and cooperative actions (van der Wel et al., 2012; Dewey et al., 2014; van der Wel, 2015; Bolt et al., 2016, 2017). Therefore, investigating the effects of TMS on these brain regions is crucial for understanding the neural mechanisms underlying SoA in both individual and joint actions. In this study, we aim to provide insights into how modulating the activity of rTPJ and lAG influences the dynamics of agency during join action during rhythmic coordination.

Current study

In the current research using rTMS, we aimed to address the following research questions. First, we intended to understand whether there is a correlation between SoA, JoP, and the joint action performance during rhythmic coordination task. Moreover, we investigated whether the inhibitory neurostimulation of rTPJ affects the quality of SoA, JoP, and the joint action performance. We further applied excitatory neurostimulation on the lAG to investigate the extent that neurostimulation affects the quality of SoA, JoP, and the joint action performance. We therefore hypothesized that inhibiting the activity of rTPJ would diminish the process of attention orientation toward the external agent and the social context, thereby reducing the social quality of SoA. This would likely manifest as a decreased sensitivity to an external agent's presence in a joint action context. Conversely, we predicted that excitatory effect of applied rTMS and induced activity of the lAG would heighten sensitivity to discrepancies between an individual's actions and their outcomes, thereby reducing the sense of individual agency by amplifying signals that indicate a mismatch between action and result.

Method and procedure

Participants

Twenty-one healthy participants were recruited from the University of Tehran's participant pool. Three participants were later excluded for technical reasons, and eighteen participants (one left-handed person, 10 women, 8 men, M_{Age}=24.6, SD_{Age}=5.25) remained for data analysis. The inclusion criteria were healthy participants over eighteen who do not have hearing and vision disorders that are problematic for the tests and did not have a prohibition to receive neurostimulation. As the first stage of the research, the candidates had to complete two parts of the Montreal Battery of Evaluation of Amusia (MBEA) test to detect disorders in musical abilities in terms of understanding the rhythm and the meter, and if their score did not reach the quorum, they would be excluded from the study. Also, any dangerous problem in receiving neurostimulation was considered a study exclusion criterion. These participants were unaware of the experimental conditions and received monetary compensation in the local currency. Subjects who participated in this study comprised both non-musicians and musicians. To ensure that they are all in a similar state of preparedness and that they will all encounter training in the same way, all participants had to accurately and completely complete every step of the training process. A statement explaining the restrictions that led to the prohibition or difficulty in receiving TMS was also sent to participants at least 24 hours prior to the scheduled time of participation in the test. Participants signed consent form, and all procedures were approved by the Ethics Committee of the Iranian Institue for Cognitive Science Studies (ICSS) (IR.UT.IRICSS.REC.1402.011) and adhered to the principles of the Declaration of Helsinki. Study was conducted in National Brain Mapping Laboratory of Iran (NBML).

Study design

A single-blind, three-way cross-over design was chosen because it involves three neurostimulations (including the sham) and requires that each participant experience all neurostimulations. By ensuring that all participants receive all three neurostimulations, this design accounts for and reduces the impact of individual biological and psychological variability. Participants were randomly assigned to three experimental groups (6 participants per group), A, B, and C following a counterbalanced design. Each group underwent cross-over neurostimulations applied to the rTPJ, lAG, and vertex (sham intervention). A minimum wash-out period of seven days was considered between each neurostimulation session to mitigate any residual effects (Nyffeler et al., 2006; Goldsworthy et al., 2012; Zito et al., 2020a; 2021) (cf., Figure 3):

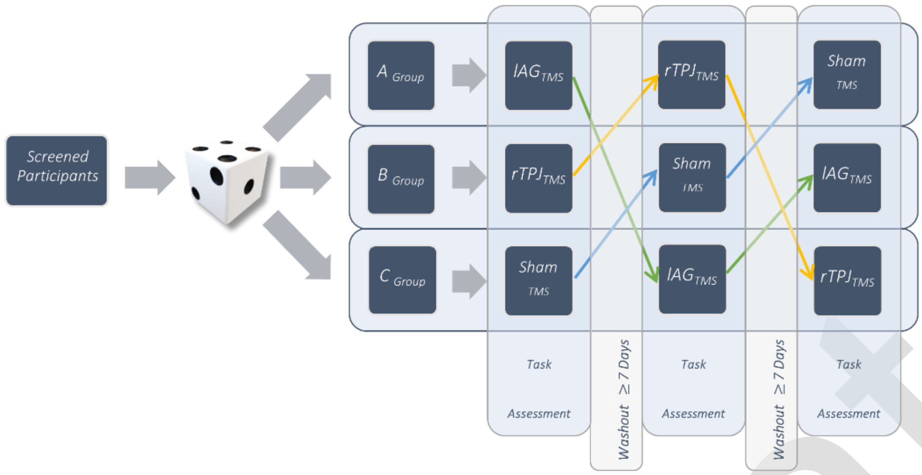

Figure 3. Three-way fully randomized cross-over design, controlled by sham intervention

Each test session lasted about 90 to 130 minutes. The pre-test, which was the participant's initial introduction to the concepts and tasks, took approximately 40 to 60 minutes. This duration could be decreased in subsequent sessions based on the participant's mastery of the concepts and tasks. The second stage involved the participant undergoing one of the three experimental neurostimulations, which lasted about 20 to 40 minutes. The third stage, known as the post-test, involved the participant practicing and completing the tasks again, lasting approximately 20 to 30 minutes.

Repetitive transcranial magnetic stimulation (rTMS)

For rTMS, the MagVenture MagPro X100 device (Denmark) with the Localite Neuro-navigation system (LOCALITE Biomedical Visualization Systems GmbH: Bonn, Germany) was utilized. Both the vacuum pillow and the coil-holding arm were used throughout every test session. Participants sat in the machine's standard chair, holding the back of their necks and under their arms, adjusting to suit their comfort levels and physical conditions. Additionally, foam earplugs were used in every real neurostimulation session to shield the volunteers' ears from the coil's loudness.

Theta burst rTMS stimulation was selected as the TMS method. Following the protocol outlined by Huang et al. (2005), the original iTBS protocol was applied for excitation in the lAG and for the sham intervention in the vertex area, while the original cTBS protocol was used for inhibition in the rTPJ area:

For inhibitory neurostimulation of the rTPJ area:

One application of cTBS:

Frequency: 3 × 50 Hz @ 5 Hz

Duration ≈ 40 sec
Trains and Pulses: 200 triplets @ 50 Hz every 200 ms, for a total of 600 pulses

For excitatory neurostimulation of the lAG area and sham intervention in the Vertex area:

One application of iTBS:
Frequency: 3 × 50 Hz @ 5 Hz
Duration ≈ 190 sec
Trains and Pulses: 200 triplets @ 50 Hz every 200 ms, with an 8 sec break every 2 sec, for a total of 600 pulses

The MCF-B70 coil (MagVenture: Denmark) was used for the inhibitory neurostimulation of the rTPJ area, and the excitatory neurostimulation of the lAG area. Furthermore, both of these neurostimulations utilized a Neuro-navigation System (with a brain atlas) and exact MNI coordinates which is as follows (cf., Figure 4): The axis used for rTPJa (Mars et al., 2012; Abe et al., 2019): [x, y, z: 59, -37, 30]; and [x, y, z: -44, -52, 42] for lAG (Zito et al., 2020b).

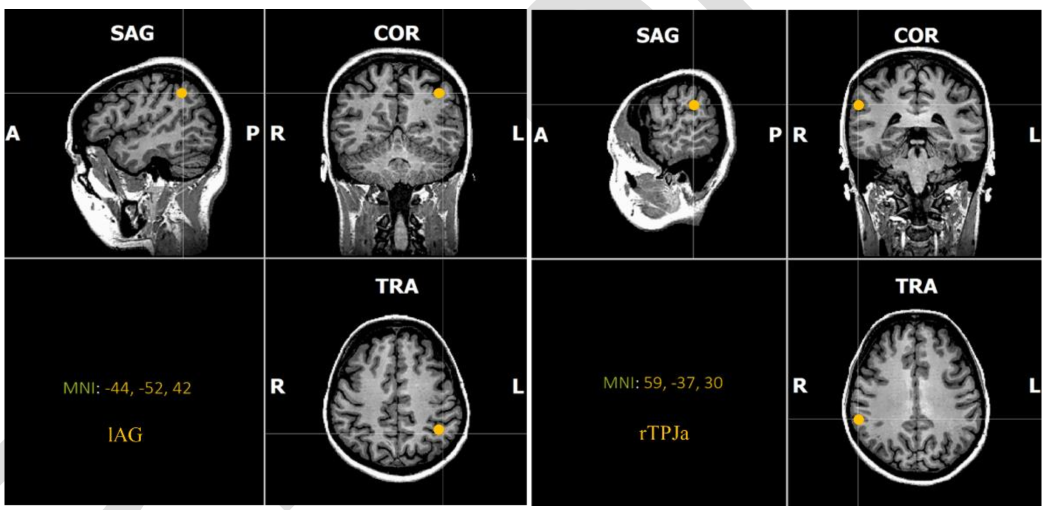

Figure 4. Right: Coordinates of the right anterior temporoparietal junction (rTPJa) (Mars et al., 2012; Abe et al., 2019); Left: Coordinates of the left angular gyrus (lAG) (Zito et al., 2020b)

Given the three-way crossover design and the fact that each participant received one sham intervention in addition to the two real neurostimulations, there was a very high likelihood that the participant would notice differences between the sham and real neurostimulations during each test session.

Previous researchers have established that the vertex area does not contain any regions or networks associated with SoA (Chambon et al., 2015; Zito et al., 2020a, 2021). Thus, one way to replicate the real conditions was to position a real coil flipped 180 degrees rotate around the X axis (Bilek et al., 2013; Zhuo et al., 2019) on the skull's vertex. In this case, the coil did not influence any brain regions relevant to SoA, but participants will experience a sensation and sound that are similar to real neurostimulation. Various available coils in the laboratory that were able to execute the iTBS protocol were examined by laboratory experts to determine which coil could produce a more stimulating feeling on the skin. Consequently, the planned protocol for a sham intervention was set on the device, and the tactile sensation produced by the coils' operation was compared with touching the palm on the back of each coil. The D-B80 coil (MagVenture: Denmark) was determined to be the best choice for a sham intervention in the vertex region. All the Neuro-navigation system's preparatory procedures and initial configurations were carried out as normal, to replicate real neurostimulation condition as much as possible. However, the coil positioning was not done by the system. The vertex area was precisely located at the intersection of the imaginary lines that were drawn from the right tragus to the left tragus and from the nasion to the inion, which finally pointed with a surgical marker. After the session, when the participants were asked how they felt (about sham intervention), they stated that they either had no sensation at all or a very slight sensation on their scalp.

The iTBS protocol was selected for the sham interventions, due to its facilitative properties. This is because the coil, even in the reverse direction, may influence the participants' peripheral scalp nerves, and thus the iTBS excitatory protocol was an appropriate choice because it will likely increase the participants' scalp sensitivity and provide them with more sensory stimulation. Conversely, it is also probable that the cTBS protocol will decrease the participants' scalp sensitivity and cause them to experience conditions that are significantly different from those of real neurostimulations, so the cTBS protocol does not appear to be an appropriate choice.

Each participant's motor threshold was determined at the start of each session for each of the three regions and for each of the three neurostimulations with the coil specific to that neurostimulation by using the visual observation of the relative frequency method (Groppa et al., 2012). To determine each participant's resting motor threshold, single pulses of varying intensities were sent to the opposite motor cortex of their dominant hand. In this approach, the device's coil was placed on the M1 region at a 45-degree angle to the sagittal axis (Brasil-Neto et al., 1992; Janssen et al., 2015). The coil's position was modified until the amplitude of the pulses peaked. Additionally, the device's output intensity was adjusted progressively in one-percent increments. The lowest intensity that could produce visible responses in the abductor pollicis brevis muscle for five out of ten consecutive pulses was the subjects' resting motor threshold (McConnell et al., 2001; Stokes et al., 2005).

The default output intensity considered for this research was equal to 120% of the resting motor threshold. To get to the amount that the participants could handle, this amount was gradually decreased by 5% each time if it was not tolerated. Any discomfort experienced in the head, neck, or face indicates that the device's output intensity is intolerable. The minimum acceptable output intensity for this research was equivalent to 80% of each person's resting motor threshold. If a participant could not tolerate this intensity or was unable to continue with the neurostimulation for any other reason, the experiment was terminated for ethical and medical reasons (Wassermann, 1998).

About the neurostimulation's side effects three reports of mild headaches were noticed. These side effects disappeared within minutes after the neurostimulation ended. A few hours following the test, three participants reported having a moderate headache, which they attributed to either our well-known extreme air pollution level on that day or exhaustion from not getting enough rest prior to the experiment. In addition, three of the participants were excluded due to medical safety considerations that made it unsafe for them to continue with the research resulting in eighteen participants for data analysis.

Rhythmic coordination task and execution

To screen participants for the tasks, they had to complete two online components of the MBEA (Peretz et al., 2003, 2008). Amusia is a disorder that impairs musical abilities and affects various executive functions necessary for understanding and producing music. The test consists of six independent sections, of which the fourth and fifth were deemed appropriate for screening the research candidates.

Before administering the tests, participants were given guidance text explaining concepts such as time, rhythm, beat, and meter and implementation tips for performing both rhythm and meter tests. Participants' questions were addressed during this briefing. Additionally, six popular and widely performed pieces of music (three marches and three waltzes) were sent to them to familiarize them with the corresponding march and waltz meters.

The fourth section of the test, which focuses on rhythmic equality, was used for the initial online screening test. The section consists of 30 brief musical pieces, each lasting less than six seconds. Each piece is played twice with a short gap in between. Participants were instructed to identify whether each pair of items is the same or different in rhythm. The test begins with two examples, including their answers, to illustrate the task (from the main set of the MBEA test).

The second online test for this screening corresponding to the fifth section of the previously described test, focuses on recognizing waltz or march meter pieces. The test consists of 30 brief musical compositions, each lasting less than 12 seconds and played only once. Participants were required to identify and state the meter of each piece. The test begins with four examples from the MBEA main test, including their responses to help participants understand the task.

Prior research (Peretz et al., 2003; Cuddy et al., 2005; Nan et al., 2010; Pfifer and Hamann, 2015; Vuvan et al., 2018) indicated that achieving at least 72 percent correct responses (within the range of 71.7 - 72.2%) on the MBEA test is cut-off score. Therefore, the participant's response sheets were reviewed, and those whose responses were below threshold were not allowed to continue with the research. These individuals were provided with an explanation of the purpose and scientific necessity of this criterion, along with verbal praise of their intention and effort to participate.

Participants received multimedia guidance, including the requisite theoretical and practical training, to prepare them to carry out the main tasks of the research. The main task used in this research was the performance of a specific musical rhythm, which was done individually (by the participant) and jointly (by the participant and the experimenter PF), before and after each neurostimulation session. This rhythm was a Drum-break created with the Steinberg HALion Sonic VST (v7.0.10) in the specialized music composition software Steinberg Cubase (v12.0.70), and the HALion Sonic SE 2 sample jazz kit plug-in. A Drum-break is a rhythmic pattern designed specifically for a drum kit that is played and heard in the background for the entire duration of a piece of music, or for a long duration of time.

The experiment included four musical tasks: Beat Keeping, Tutti, Odd Beats, and Even Beats. Odd Beats and Even Beats were joint tasks, whereas Beat Keeping and Tutti were solo tasks. Each solo task took 90s to complete and record, and each joint task takes 120s, including the time required to play the example at the start of each task. The extended duration of the tasks was designed to allow participants to identify and address their areas of weakness over time. In addition, this period provided a chance to learn and adapt to their partners' behavior in joint tasks. Research indicates that longer task duration can improve symmetrical adaptation during joint actions more efficiently (Konvalinka et al., 2014; Bolt et al., 2016).

In the Beat Keeping task, participant's role was to maintain a beat at tempo of 120 beats per minute, with equal intervals between beats (one beat = half a second). A guidance sample of twelve beats was played at the start of the task, and the participant began their task immediately after this sample finished. This test was designed to assess how neurostimulation affected brain functions related to time perception and time keeping.

In the Tutti task, participants were required to perform the Drum-break at a tempo of 60 beats per minute. The entire Drum-break was played once at the beginning of the task, after which participants had to perform it instantaneously. This test was designed to assess the impact of neurostimulation on alterations in brain functions related to rhythm production and perception.

The two joint action tasks that constituted the core of the research were Odd Beats and Even Beats. These tasks were similar to the Tutti task but were systematically divided into two interdependent parts involving both the participant and the experimenter. They were designed to assess brain functions related to cooperation, coordination, and SoA during shared activities, as well as the efficacy of neurostimulation on these functions. During these tasks, each participant took turns performing specific parts of the Drum-break resulting in a coordinated performance of the Drum-break at a tempo of 60 beats per minute. In the Odd Beats task, the participant began the

Drum-break by performing the odd beats (parts "a"), while the experimenter performed the even beats (parts "b"). Conversely, in the Even Beats task, the experimenter initiated the Drum-break with the Odd Beats (parts "a"), while the participant performed the even beats (parts "b"). Thus, in these two tasks using the same materials, the participant and experimenter alternated roles. Each task required them to perform different parts of the Drum-break in a coordinated and alternative manner. This design was crucial for examining the asymmetry in the Drum-break and understanding how individual’s SoA and performance are affected by their role leading or following positions (Bolt et al., 2016).

This rhythm can be divided according to each measure, beat, and note. Previous studies have demonstrated that symmetry in participants' coordination and cooperation is crucial for developing a sense of joint agency (Pacherie, 2012; Pokropski, 2015). When engaging in joint actions that require more symmetrical coordination, individuals were motivated to adopt a "we-mode" and pay closer attention to each other's actions (Gallotti & Fritt, 2013).

The Drum-break used for this research consisted of a two-measure rhythm. If this rhythm were divided by measures, with each measure assigned alternately to one participant, the necessary symmetry for coordination would be compromised due to the long intervals. This delay would hinder consistent coordination between participants. Research suggests that people coordinate more effectively when they can predict each other’s actions (Keller et al., 2007; Loehr & Palmer, 2011; Zamm et al., 2016). Symmetrical coordination enhances predictability, leading to a stronger sense of joint agency when participants can accurately anticipate both their own and others’ actions (Pacherie, 2012; Bolt et al., 2016). Symmetric coordination reduces variability in timing of actions and increases predictability; which is positively correlated with an enhanced sense of joint agency (Vesper et al. 2011; Bolt et al., 2016). Dividing the rhythm by notes would further disrupt coordination due to the varying durations of notes, causing inconsistencies in action timing and reducing predictability. The short intervals between participants' performances would also eliminate opportunities for predicting and coordinating actions effectively. Therefore, dividing the rhythm based on beats emerges as the optimal solution, achieving the necessary balance for effective coordination.

The tempo for all tasks, particularly the Beat Keeping task, was set with consideration for the spontaneous tempo of human locomotion, was set at 120 beats per minute (one beat equals half a second). Research has shown that human step rates and vertical head movement rates during daily activities reflect a dominant component of around 2 Hz (Murray et al., 1964; MacDougall and Moore, 2005; Styns et al., 2007). This component is consistent across different gender, age, height, weight, or body mass index. This locomotion tempo aligns with the spontaneous tempo tapping with metronome beats (Mishima, 1956; Fraisse, 1982; Waters et al., 1988) and finger tapping (Frischeisen-Köhler, 1933; Farnsworth et al., 1934; Kay et al., 1987; Collyer et al., 1994; Moelants, 2002), both of which average 2 Hz and are closely correlated with human walking locomotion rates (Harrison, 1941; Mishima, 1965). The intrinsic pace of central pattern generators, whose existence in humans can only be inferred indirectly, may be reflected in this spontaneous tempo and relatively consistent tempo of locomotion (Marder, 2001; Dietz, 2003). Furthermore, the highest level of basal ganglia activity appears when we listen to music which its tempo is 120 beats per minute (Riecker et al., 2003, 2006). According to a thorough analysis of Western music from the second half of the 20th century, most composers have a preference for a tempo of 120 beats per minute (Moelants, 2002). Another study on rhythmic patterns performed using a drums instrument found a U-shaped relationship between tempo and groove scores. A musical feature connected to movement and dancing is called groove (Madison, 2006; Madison et al., 2011; Janata et al., 2012; Stupacher et al., 2013). The study identified an optimal tempo range for groove development, suggesting that 107 to 126 beats per minute is ideal (Etani et al., 2018).

The Drum-break used in the study's tasks was chosen based on findings from research on the relationship between music, bodily movement, and pleasure during both performance and listening. Enjoying music and our emotional reactions to it are linked to our expectations and predictions about music (Meyer, 1956; Huron, 2006; Vuust & Frith, 2008; Vuust & Kringelbach, 2010; Gebauer et al., 2012), and apparently predictability of rhythm and its complexity are important variables for the process of music enjoyment (North and Hargreaves, 1995, 1997, 1998; Keller and Schubert, 2011). Groove intensity is positively connected with beat saliency and sub beat deviations (Madison et al., 2011). However, the feeling of satisfaction, pleasure, and groove can be diminished by microtiming (Davies et al., 2013), a term used to describe deviations from rhythmic isochrony on a time scale of a few milliseconds (Witek et al., 2014). In contrast, syncopation, which involves shifting the emphasis and weight of strong and weak beats (Longuet-Higgins and Lee, 1984; Temperley, 1999; Vuust et al., 2022), can increase the experience of satisfaction, pleasure and groove (Greenwald, 2002; Gioia, 2011). However, this effect has appeared only with moderate degree of syncopation (Witek et al., 2014; Matthews et al., 2022; Spiech et al., 2022). Repetition is crucial to groove because it gradually increases the predictability of complex features like syncopation, which in turn enhances sensorimotor synchrony (Pressing, 2002; Madison et al., 2011; Janata et al., 2012).

The Drum-break chosen for the task in this study was one of the 50 analyzed for groove in research by Witek et al. (2014). Specifically, the Drum-break from Roy Ayers' Boogie Back, a two-measure piece in 4⁄4 meter, was selected from a collection of 34 genuine music Drum-breaks, which featuring Bass-drum, Snare-drum and Hi-hats (cf., Figure 5).

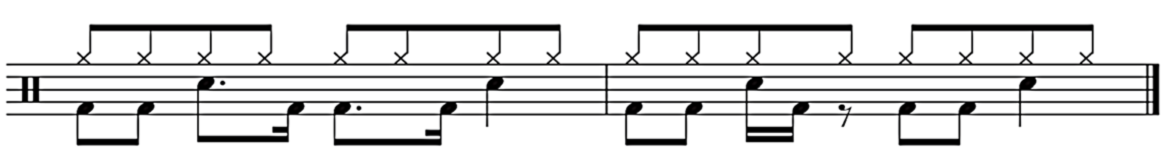

Figure 5. Drum-break sheet music of the Boogie back by Roy Ayers

This Drum-break contains no microtiming. Previous studies have shown that the relationship between syncopation index and groove follows an inverted U-shaped, meaning that only a moderate level of syncopation can improve sensorimotor coordination and the overall sense of satisfaction and enjoyment of music. Of the 34 drum-breaks analyzed, only 15 fell within the medium syncopation range, that this chosen Drum-break having the least syncopation. The decision to use this Drum-break was primarily based on its appropriate syncopation index. Additionally, when calculating the syncopation index, the difference in sound resonance across various drum instruments was considered, alongside a comparison of the emphasis and metric weight differences between rests and notes (Lerdahl & Jackendoff, 1983; Ladinig, 2009; Ladinig et al., 2009; Witek et al., 2014).

This Drum-break consists of two measures, which exhibit predictability and repetition since they are nearly identical, differing only three parts. Its structure also incorporates some rhythmic complexity and sub-beat variations through Quarter-, Eighth-, and Sixteenth note. A distinct beat saliency is achieved by employing the Hi-hats on both strong and weak beats, with each beat also featuring either the Bass-drum or Snare-drum. The groove quality is further enhanced by using the Bass-drum on more than 70% of the notes, particularly on strong and semi-strong beats (Burger et al., 2013; Van Dyck et al., 2013; Hove et al., 2014; Lenc et al., 2018; Cameron et al., 2022).

One of the primary reasons for selecting this Drum-break was that it was the only one without an off-beat and a sixteenth-rest among all other Drum-breaks. Off-beat refers to notes that are absent from their expected strong positions within the measure. The Sixteenth note, being one of the smallest time divisions, complicates beat counting and performance. Their rest form further compounds this difficulty by requiring not only the counting of the beats but also the inhibition of its execution. In summary, off-beats can diminish beat saliency: and sixteenth rests can make performance challenging.

Finally, modifications were made to the main Drum-break with a condition that the syncopation index remain constant, to facilitate quicker preparation and more consistent performance by all participants. To enhance beat saliency, and simplify the task, two sub-beats were removed, and the sixteenth rests were eliminated (cf., Figure 6). Moreover, the Drum-breaks tempo was adjusted to 60 beats per minute to ensure smoother performance. The Hi-hats, which are played twice per beat, (one beat equating to one second), were set at a tempo of 120 beats per minute, while the other notes were played at 60 beats per minute. This can induce the spontaneous tempo of locomotion to the participants and keep the groove quality acceptable.

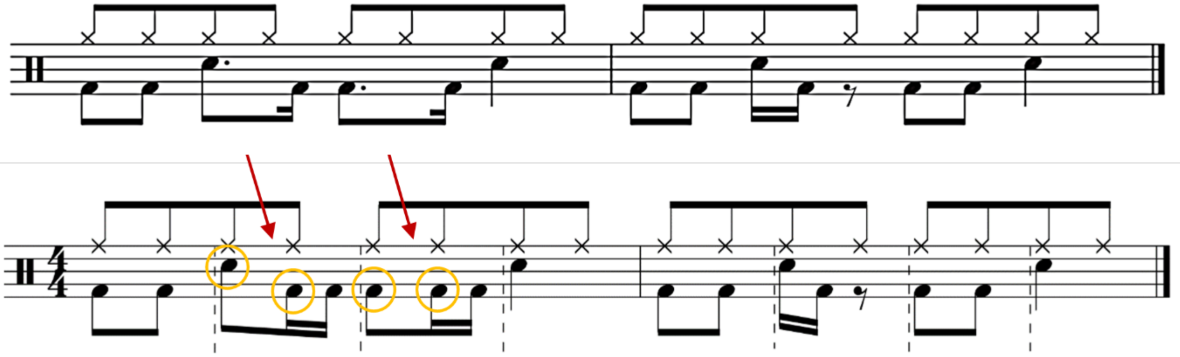

Figure 6. Up: original Drum-break; Bottom: Changes applied to the original Drum-break

The notes represented by the symbol "x" indicate where the Hi-hats strike; these notes are handled by the software and were not performed by participants. The software plays these hi-hat notes as the foundation of the Drum-break, while participants are responsible for performing the remaining notes. The Bass-drum is represented by the notes between the first and second lines (from the bottom), and the Snare-drum is represented by the notes between the third and fourth lines.

Regardless of instrument, the rhythm's odd and even beats are split into two parts, "a" and "b". Dotted lines are used to split the beats of the Drum-break rhythm alternately. This results in eight beats in the Drum-break, with part "a" consisting of odd beats and part "b" consisting of even beats. Each beat is assigned either to the participant or the experimenter, requiring them to perform alternatively and continuously. Furthermore, each note of the Drum-break is marked with letters "R" and "L", indicating the right or left index finger should be used, respectively (cf., Figure 7). Note that these markings are not present on the notes provided to participants on the test day; they are solely for learning how to perform the Drum-break.

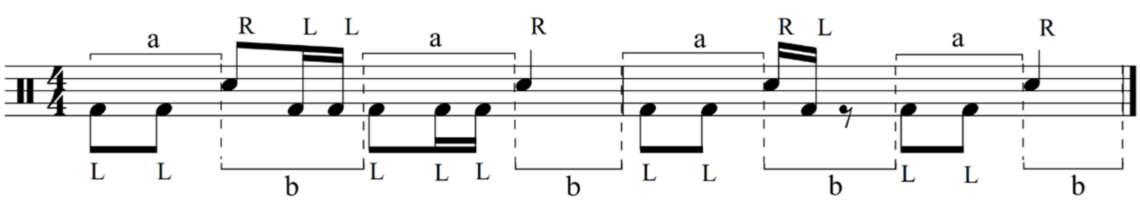

Figure 7. Beat division and fingering of Drum-break notes

For each "a" and "b" participant, the parts are going to be as follows (cf., Figure 8):

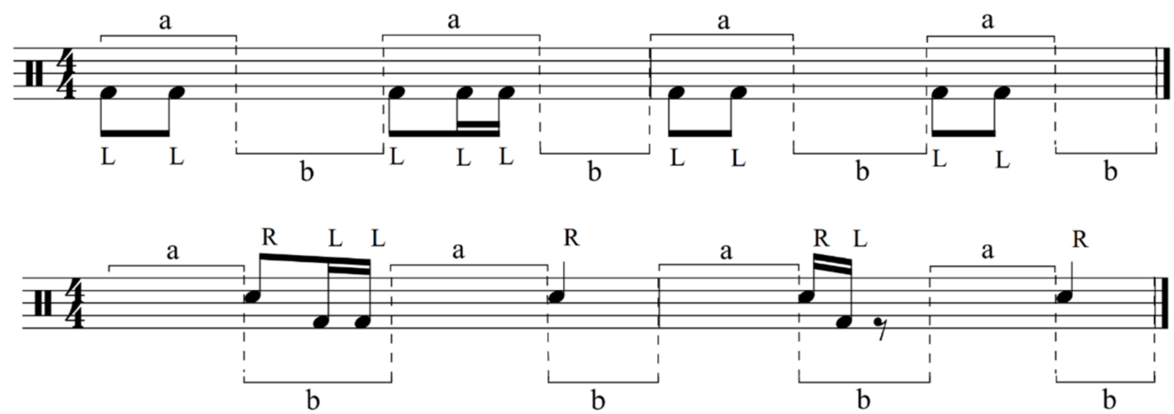

Figure 8. Up: "a" parts; Bottom: "b" parts

Finally, on test day, participants were presented with notes where the direction of the stem served as a marking and partitioning method. Participants were instructed to perform only the notes that their stems pointed towards them, while the notes with stems facing the opposite direction were assigned to the experimenter.

For the Tutti task, which is a solo task, the stems of all notes are directed towards the participant (cf., Figure 9):

Figure 9. Sheet music for Tutti task

The notes for the Even Beats and Odd Beats tasks are identical to those of the Tutti task, with the difference that in the Odd Beats task, the participant had to perform the odd beats or "a" parts, and therefore the odd beats stems were towards participant, and the even beats stems were towards the experimenter (cf., Figure 10):

Figure 10. Sheet music for Odd Beats task

Since participants in the Even Beats task had for performing the even beats or "b" parts, the stems of these notes were pointed towards them and conversely, the stem of the notes corresponding to the odd beats were pointed towards the experimenter (cf., Figure 11):

Figure 11. Sheet music for Even Beats task

On the experiment's day, the participant and experimenter were seated on opposite sides of a table about a meter apart while performing and recording the tasks. Participants were sat while their hands facing the other side, and their forearms were in flat position on the table. The data collection hardware for the Drum-break was positioned about 40 cm away from each participant. Except for the Beat Keeping task, which had to be performed mentally and did not need a printed guide, each of the remaining three tasks came with a 7 x 21 cm music sheet. This sheet, which displayed the task name, and the full-page Drum-break musical score, was positioned between the participants and the hardware, directly in front of them. Anyone could choose whether to refer to it.

There were three stages in every triple experimental condition. The tasks were trained and performed in the first (pre-test) and third (post-test) stages, while participants went under one of the three neurostimulation experimental conditions in the second stage. Every condition listed below was applied, one by one, to each of the four tasks in the first and third stages. Initially, participants received direct training on how to perform it. After that, depending on the type of task, participants would practice it solo or in pairs. Training lasted until the participants' performance was at an acceptable level. The performance of participants would typically show a noticeable improvement after a bit of training and would then remain at a qualitative level. In this case, the training concluded with the experimenter's decision and the participant's feedback. Because the participants' skill levels varied so much, there were no specific limits, in terms of time and number of repetitions, to the training.

None of the tests provided audible or visual signals that participants could be utilized to correct their performance when they made errors. The task was executed in any manner and with any degree of error, except for situations in which participant's awareness and concentration were interfered with by external factors or in which the task's execution was beyond their control and they were unable to follow up or proceed. Participants had to use a seven-point Likert scale to report their SoA and JoP at the end of both the first and third stages of all tasks.

Each participant was always in the experimental position, whereas the experimenter was in the control position, which was not subject to any neurostimulation. Additionally, the experimenter had to perform the Drum-break correctly and attempt to prevent any intentional or unintentional rhythm changes to create conditions with the least number of distracting factors. It should be noted that previous studies have shown that human-to-human interaction is the only way to form the sense of joint agency, and that human-to-computer interaction inhibits the processes involved in mediating the sense of joint agency (Obhi and Hall, 2011), and this indicates the human-centeredness of the sense of joint agency (Limerick et al., 2014; Sahaï et al., 2019). It has also been found that when interacting with non-human agents, people's implicit SoA is disturbed and a bias causes over-attribution of their own role and contribution in joint action (Grynszpan et al., 2019). Therefore, the experimenter's presence was necessary rather than the use of a computer program or pre-recorded music to generate real social context conditions during the joint task, and it was not possible to use a non-human agent for the partnership.

The tasks were performed and recorded in a reasonably quiet room. No one else was present at the task execution location except the participant and the experimenter, and there were no visual stimuli from moving people or objects. The use of closed-back headphones allowed for some ear isolation and reduced exposure to noise. Participants were questioned to make sure there wasn't a problem. If participants' capacity to concentrate was disrupted by any external factors, the task was stopped and restarted after the disruption was eliminated.

Measurements

Measurement of Sense of agency (SoA)

A seven-point Likert scale scroll bar, ranging from sense of self agency (labeled on the left side of the scroll bar) to sense of joint agency (labeled on the right side of the scroll bar), was used to measure and quantify the quality of SoA of the participants. They were instructed to move the scroll bar to the left if they felt more in charge of the task, and if they feel the charge of the task jointly with the experimenter and themselves, move the scroll bar to the right in the same proportion. To avoid bias in the meaning of numbers, no Likert scale numbers were displayed.

Measurement of Judgment of performance (JoP)

A seven-point Likert scale scroll bar, ranging from bad performance (labeled on the left side of the scroll bar) to good performance (labeled on the right side of the scroll bar), was also used to measure and quantify the participants' JoP scores throughout task execution. They were instructed to move the scroll bar to the left if they think that the task was executed badly, and if they think that the execution of the task was good, move the scroll bar to the right in the same proportion. To avoid bias in the meaning of numbers, no Likert scale numbers were displayed.

Data collection tools

The task data recording software was programmed in Python (v3.10.11) and executed by Python (v3.10.11), both of which were developed in the Microsoft Visual Studio Code (v1.91.1). When the coded software was executed, a window appeared where details could be entered, such as the participant's name, the experiment's phase (pre-test or post-test), the region that would receive brain stimulation, and the type of task. The first finger tap initiated the recording of rhythmic data with the following details: agent (participant or experimenter), fingering (right or left hand's index finger), and action time (in seconds with two decimal places). In addition to the tasks being recorded by the coded software, the tasks were recorded in audio format by Steinberg Cubase (v12.0.70), a specific music composition software. This allowed for an audit of the performances' audio and schematics for any follow-up research. The Microsoft Windows 11 Pro versions 23H1 and 23H2 operating systems were utilized to run all 64-bit versions of the applications used in this study. The Steinberg Generic Lower Latency ASIO driver (v1.0.30) would make possible the lowest delay under these hardware and software conditions, which was determined to be a maximum of 10 milliseconds between the actual time of pressing the hardware keys (input) and the time of recording them in the software (output).

An 8 GB random access memory and an Intel Core i5 (8350U @ 1.70 GHz) processor were features of the Microsoft Surface Pro 6 commercial (model 1796) device that was utilized for recording and analyzing all the research data. Except for what was required for tests, no software ran while tasks were being performed. The voltage and amp protector were used to connect the computer to the power outlet, and Windows' power mode settings were adjusted to the maximum performance mode. The tasks could be listened to entirely simultaneously with the same loudness and sound quality thanks to two JBL Quantum 100 headphones that could play the audio range of sounds required and used in the tasks. The headphones were connected to the computer via a UGREEN interface cable. KORG NanoPad 2 drum-pad studio hardware was also used to record the rhythmic data of participants' finger beats.

Data Preparation

The reference table was used to compare all software output data. The agent (participant or the experimenter), fingering (right or left hand's index finger), action time and action time interval. To determine the performance status of participants, the action time error and the number of errors in the pre-test and post-test of all tasks were calculated. To calculate the action time error, the difference between the action time of each note and the reference action time of the same note was calculated, and the total absolute value of the difference of all notes was considered as the amount of action time error. In order to calculate the number of errors, the sequence of performed notes was compared with the sequence of reference notes of the same task - in terms of note rhythm, note performer and note fingering - and by examining the pattern of these sequences, the unperformed or incorrectly performed notes of the participants were determined as total number of errors. It should be noted that these calculations were done for each task of each person and each neurostimulation session separately so that the results of these calculations can be prepared for statistical analysis of individual variables.

In addition to the participants' performance status, their SoA scores and JoP scores in the pre-test and post-test conditions of all tasks were analyzed in terms of the significance of the considered changes, based on different variables (neurostimulation, task type and different sessions). To investigate the effect of neurostimulations on the multiple relationship of each of the dependent variables, the correlation of all these cases in the general pre-test conditions of all neurostimulations, and the post-test of each neurostimulation were calculated separately to check the significant changes of correlations in different experimental conditions.

Data Analysis

The dataset that was generated and analyzed during the current study will be made available on publication in an Open Science Framework repository on OSF.io. Inferential statistics were performed with R (R Core Team 2023) and the Jamovi software environment version 2.5.6 (The Jamovi project 2024). All relevant R packages (v4.4.1; RStudio 2024.04.2+764) and related references are listed in the supplement. If not stated differently, $p < 0.05$ was considered as significant.

Descriptive results depending on each neurostimulation session

A small difference in the average sum of values for each dependent variable was observed across the different neurostimulation sessions. This indicates that the neurostimulation sessions may have had a slight impact on the outcomes measured, although the differences were not substantial. The details of these averages can be found in Table 1, which summarizes the mean scores for each dependent variable under each neurostimulation condition.

This observation suggests that while the neurostimulation interventions may not have led to pronounced effects on the dependent variables, they could still influence the outcomes in a nuanced manner, warranting further exploration in future analyses.

Table 1. Descriptives values for neurostimulation regions

	Neurostimulation Region	Sense of Agency of the Solo tasks	Judgment of Performance of the Solo tasks	Sense of Agency of the Joint Tasks	Judgment of Performance of the Joint Tasks	Action Time Errors	Number of Errors
Mean	rTPJ	2.1	5.01	5.25	5.18	8.3	2.21
	lAG	1.96	4.79	5.32	5.1	9.06	2.21
	Vertex	1.96	4.94	5.35	5.07	8.69	2.26
Standard deviation	rTPJ	0.966	1.25	1.55	1.09	3.51	3.65
	lAG	0.956	1.4	1.34	1.25	4.47	3.34
	Vertex	0.911	1.45	1.3	1.47	4.05	3.53

The comparison of values in Table 2 indicates a notable reduction in both the action time error and the number of errors throughout the sessions. Additionally, the JoP scores exhibited a corresponding increase. These changes collectively suggest that participants' performance in the tasks has improved over time. This improvement may reflect the effects of the neurostimulation sessions on participants' abilities, leading to more accurate task execution and enhanced self-assessment of performance. Such findings underscore the potential efficacy of the interventions in optimizing task performance, indicating a positive trajectory in participant outcomes as sessions progressed. Further analyses could provide deeper insights into the mechanisms behind these improvements.

Table 2. Descriptive based on sessions

	Session	Sense of Agency of the Solo tasks	Judgment of Performance of the Solo tasks	Sense of Agency of the Joint Tasks	Judgment of Performance of the Joint Tasks	Action Time Errors	Number of Errors
Mean	1	1.96	4.68	5.43	4.96	9.86	3.11
	2	2.03	4.96	5.44	5.04	8.2	2.02
	3	2.03	5.11	5.04	5.35	7.99	1.56
Standard deviation	1	0.999	1.52	1.25	1.33	4.94	4.01
	2	0.919	1.26	1.25	1.32	3.59	3.2
	3	0.919	1.3	1.62	1.15	3.1	3.05

Pearson correlation analysis was conducted to examine the relationships between SoA in solo tasks, JoP in solo tasks, SoA in joint tasks, JoP in joint tasks, action time error, and the number of errors. To further investigate the potential changes in SoA and JoP during joint action and whether this effect is modulated by rTMS, a generalized linear model (GLM) was employed. In this model, SoA and JoP for each task, as well as performance variables (action time error and number of errors), were included as dependent variables, with neurostimulation region (rTPJ, lAG, Vertex) as a between-subject factor.

Correlation of variables values: Baseline and Post-test analyses

Baseline correlations of variables

The results revealed a significant negative correlation between JoP in solo tasks and action time error ($r = -0.237$, $p = 0.014$). A positive correlation was found between SoA in joint tasks and JoP in joint tasks ($r = 0.341$, $p < 0.001$). Additionally, significant negative correlations were observed between JoP in joint tasks and action time error ($r = -0.284$, $p = 0.003$), as well as between JoP in joint tasks and the number of errors ($r = -0.286$, $p = 0.003$). However, no significant correlations were found between SoA in solo tasks and the number of errors ($r = -0.228$, $p = 0.097$), or between JoP in solo tasks and the number of errors ($r = -0.232$, $p = 0.092$). Furthermore, no significant correlations were observed between SoA in solo tasks and JoP in solo tasks ($r = -0.116$, $p = 0.233$), between SoA in solo tasks and action time error ($r = -0.070$, $p = 0.472$), between SoA in joint tasks and action time error ($r = -0.041$, $p = 0.674$), or between SoA in joint tasks and the number of errors ($r = 0.026$, $p = 0.791$).

Correlations after cTBS applied to right temporoparietal junction (rTPJ)

The results revealed a significant negative correlation between JoP in solo tasks and the number of errors ($r = -0.591$, $p = 0.010$). A negative correlation was also observed between JoP in joint tasks and action time error, approaching significance ($r = -0.318$, $p = 0.059$). Additionally, a marginally significant negative correlation was found between SoA in solo tasks and action time error ($r = -0.306$, $p = 0.070$), as well as between JoP in solo tasks and action time error ($r = -0.305$, $p = 0.071$). Conversely, no significant correlations were found between SoA in solo tasks and JoP in solo tasks ($r = -0.203$, $p = 0.235$), between SoA in solo tasks and the number of errors ($r = -0.037$, $p = 0.885$), between SoA in joint tasks and JoP in joint tasks ($r = 0.085$, $p = 0.623$), between SoA in joint tasks and action time error ($r = -0.073$, $p = 0.674$), between SoA in joint tasks and the number of errors ($r = 0.038$, $p = 0.825$), or between JoP in joint tasks and the number of errors ($r = -0.274$, $p = 0.106$).

Correlations after iTBS applied to left angular gyrus (lAG)

The results showed a significant negative correlation between SoA in solo tasks and JoP in solo tasks (r = -0.473, p = 0.004). Significant negative correlations were also found between JoP in joint tasks and action time error (r = -0.502, p = 0.002) as well as between JoP in joint tasks and the number of errors (r = -0.472, p = 0.004). A marginally significant negative correlation was observed between JoP in solo tasks and the number of errors (r = -0.423, p = 0.080). No significant correlations were found between SoA in solo tasks and action time error (r = 0.005, p = 0.978), between SoA in solo tasks and the number of errors (r = -0.133, p = 0.600), between JoP in solo tasks and action time error (r = -0.257, p = 0.131), between SoA in joint tasks and JoP in joint tasks (r = 0.152, p = 0.375), between SoA in joint tasks and action time error (r = 0.197, p = 0.250), or between SoA in joint tasks and the number of errors (r = 0.008, p = 0.964).

Correlations after Sham iTBS applied to Vertex

The results revealed a marginally significant negative correlation between SoA in solo tasks and JoP in solo tasks (r = -0.298, p = 0.077), and between JoP in solo tasks and action time error (r = -0.290, p = 0.086). Additionally, a marginally significant positive correlation was found between SoA in joint tasks and JoP in joint tasks (r = 0.318, p = 0.059). Conversely, no significant correlations were observed between SoA in solo tasks and action time error (r = -0.118, p = 0.492), between SoA in solo tasks and the number of errors (r = 0.115, p = 0.649), between JoP in solo tasks and the number of errors (r = -0.112, p = 0.658), between SoA in joint tasks and action time error (r = 0.122, p = 0.478), between SoA in joint tasks and the number of errors (r = 0.117, p = 0.497), between JoP in joint tasks and action time error (r = -0.093, p = 0.590), or between JoP in joint tasks and the number of errors (r = -0.180, p = 0.293).

Changes in SoA, JoP, and Performance Errors Based on Neurostimulation Regions

Sense of Agency (SoA) Scores

For the Beat Keeping task, post-test SoA scores showed positive changes. However, a GLM analysis revealed no significant effect of Session on SoA as the dependent variable ($R^2 = 0.019$, adj. $R^2 = 0.000$, $F(1, 34) = 0.676$, $p = 0.417$). Similarly, for the Tutti task, the GLM revealed no significant effect ($R^2 = 0.004$, adj. $R^2 = 0.000$, $F(1, 70) = 0.126$, $p = 0.724$), although post-test SoA scores showed positive changes. In the Odd Beats task, post-test SoA scores exhibited negative changes, but the GLM also revealed no significant effect ($R^2 = 0.026$, adj. $R^2 = 0.000$, $F(1, 34) = 0.917$, $p = 0.345$). For the Even Beats task, while positive changes in post-test SoA scores were observed, the GLM indicated no significant effect ($R^2 = 0.003$, adj. $R^2 = 0.000$, $F(1, 70) = 0.102$, $p = 0.751$).

The GLM analysis revealed no significant effect of cTBS on the SoA of the Beat Keeping task, with negative changes observed post-test ($R^2 = 0.002$, adj. $R^2 = 0.000$, $F(1, 34) = 0.084$, $p = 0.774$). For the Tutti task, positive changes in SoA were observed post-test, but the GLM was non-significant ($R^2 = 0.037$, adj. $R^2 = 0.009$, $F(1, 34) = 1.31$, $p = 0.261$). In the Odd Beats task, negative changes in SoA were observed with no significant effect in the GLM ($R^2 = 0.015$, adj. $R^2 = 0.000$, $F(1, 34) = 0.525$, $p = 0.474$). The Even Beats task showed no significant changes ($R^2 = 0.000$, adj. $R^2 = 0.000$, $F(1, 34) = 1.20e\text{-}29$, $p = 1.000$).

Judgment of Performance (JoP) Scores

The Beat Keeping task showed negative changes in JoP post-test with no significant GLM effect ($R^2 = 0.005$, adj. $R^2 = 0.000$, $F(1, 34) = 0.180$, $p = 0.674$). In the Tutti task, positive changes were observed post-test, but again, the GLM revealed no significant effect ($R^2 = 0.003$, adj. $R^2 = 0.000$, $F(1, 34) = 0.115$, $p = 0.737$). The Odd Beats task also showed positive post-test changes, with a non-significant GLM ($R^2 = 0.000$, adj. $R^2 = 0.000$, $F(1, 34) = 0.00378$, $p = 0.951$), and similarly, the Even Beats task exhibited positive changes with a non-significant GLM ($R^2 = 0.012$, adj. $R^2 = 0.000$, $F(1, 34) = 0.427$, $p = 0.518$).

Performance (Action Time Error and Number of Errors)

The GLM for action time error in the Beat Keeping task post-test revealed no significant effect ($R^2 = 0.005$, adj. $R^2 = 0.000$, $F(1, 34) = 0.180$, $p = 0.674$). Positive changes in the Tutti task action time error were noted, but the model remained non-significant ($R^2 = 0.003$, adj. $R^2 = 0.000$, $F(1, 34) = 0.115$, $p = 0.737$). The Odd Beats task saw positive post-test changes, with no significant effect ($R^2 = 0.000$, adj. $R^2 = 0.000$, $F(1, 34) = 0.00378$, $p = 0.951$). The Even Beats task showed positive changes, with a non-significant GLM ($R^2 = 0.012$, adj. $R^2 = 0.000$, $F(1, 34) = 0.427$, $p = 0.518$). Similarly, the number of errors in the Tutti task improved post-test with no significant effect ($R^2 = 0.002$, adj. $R^2 = 0.000$, $F(1, 34) = 0.0613$, $p = 0.806$), and for the Odd Beats task, the GLM was non-significant despite positive changes ($R^2 = 0.023$, adj. $R^2 = 0.000$, $F(1, 34) = 0.818$, $p = 0.372$). Lastly, the Even Beats task also demonstrated positive changes in the number of errors, but the GLM was not significant ($R^2 = 0.029$, adj. $R^2 = 0.001$, $F(1, 34) = 1.03$, $p = 0.317$).

Intermittent Theta Burst Stimulation (iTBS) Applied to the Left Angular Gyrus (lAG)

Sense of Agency (SoA) Scores

In the Beat Keeping task, the post-test changes in SoA were negative, and the GLM was not significant ($R^2 = 0.009$, adj. $R^2 = 0.000$, $F(1, 34) = 0.298$, $p = 0.589$). For the Tutti task, negative changes in SoA were also observed, with no significant effect in the GLM ($R^2 = 0.003$, adj. $R^2 = 0.000$, $F(1, 70) = 0.105$, $p = 0.748$). In the Odd Beats task, post-test SoA scores exhibited negative changes, but the GLM was again non-significant ($R^2 = 0.027$, adj. $R^2 = 0.000$, $F(1, 34) = 0.953$, $p = 0.336$). Conversely, the Even Beats task showed positive changes, though the GLM was not significant ($R^2 = 0.075$, adj. $R^2 = 0.048$, $F(1, 70) = 2.77$, $p = 0.105$).

Judgment of Performance (JoP) Scores

In the Beat Keeping task, the post-test JoP scores showed positive, yet non-significant, changes ($R^2 = 0.027$, adj. $R^2 = 0.000$, $F(1, 34) = 0.948$, $p = 0.337$). The Tutti task also showed positive changes in JoP post-test, but the GLM revealed no significant effect ($R^2 = 0.009$, adj. $R^2 = 0.000$, $F(1, 34) = 0.324$, $p = 0.573$). Similarly, in the Odd Beats task, positive post-test changes were observed, but the GLM model was not significant ($R^2 = 0.027$, adj. $R^2 = 0.000$, $F(1, 34) = 0.959$, $p = 0.334$). Positive changes were also seen in the Even Beats task, though the GLM remained non-significant ($R^2 = 0.067$, adj. $R^2 = 0.039$, $F(1, 34) = 2.43$, $p = 0.128$).

Performance (Action Time Error and Number of Errors)

In the Beat Keeping task, the GLM for action time error post-test revealed no significant effect, though positive changes were observed ($R^2 = 0.001$, adj. $R^2 = 0.000$, $F(1, 34) = 0.0425$, $p = 0.838$). Action time errors in the Tutti task worsened, but the GLM was not significant ($R^2 = 0.002$, adj. $R^2 = 0.000$, $F(1, 34) = 0.0788$, $p = 0.781$). In the Odd Beats task, action time errors improved, though the GLM remained non-significant ($R^2 = 0.004$, adj. $R^2 = 0.000$, $F(1, 34) = 0.144$, $p = 0.707$), while the Even Beats task saw negative changes in action time error, again with no significant effect ($R^2 = 0.003$, adj. $R^2 = 0.000$, $F(1, 34) = 0.114$, $p = 0.737$).

Carryover effect of sessions (learning the tasks)

In the case of any of the variables of SoA and JoP, the power of the GLM model is not significant and it cannot extract significant changes, which means the absence of significant and effective changes. But the GLM model shows significant changes regarding the action time error and the number of errors. The analysis of carryover effects across sessions indicated that for the variables related to the SoA and JoP, the GLM did not demonstrate significant power. Specifically, the GLM models failed to extract meaningful changes in these variables, suggesting that there were no significant or effective changes in participants' perceptions of agency or performance across the sessions. In contrast, the GLM models did reveal significant changes concerning performance metrics, specifically action time error and the number of errors. This indicates that while participants did not experience notable changes in their subjective feelings of agency or judgment of their performance, there were measurable improvements in their task performance over the sessions.

Sense of Agency (SoA) scores

The results of the GLM for examining changes in the SoA scores for the solo tasks revealed no significant effect ($R^2 = 0.012$, adj. $R^2 = 0.000$, $F(5, 210) = 0.125$, $p = 0.776$) (cf. Figure 12). This indicates that neurostimulation did not lead to any statistically significant changes in SoA for the solo tasks, as the model failed to explain a meaningful amount of variance in the post-test scores.

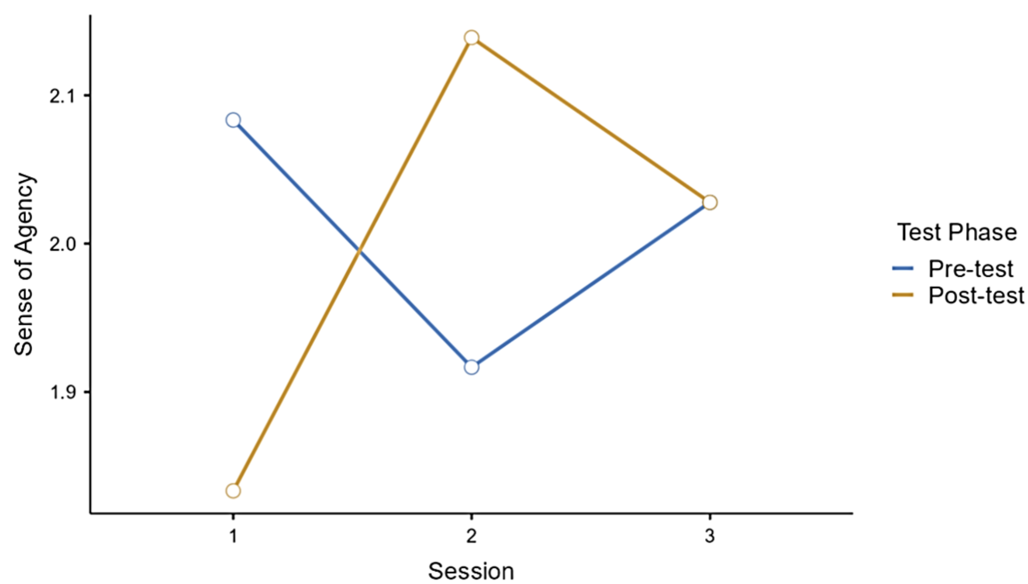

Figure 12. Changes in the sense of agency scores of the solo tasks at different sessions

It is not possible to examine the changes in the scores of SoA of the joint tasks due to the non-significant of the GLM model ($R^2 = 0.02$, adj. $R^2 = 0.000$, $F(5, 210) = 0.843$, $p = 0.521$) (cf., Figure 13).

The analysis of changes in the scores of the SoA for joint tasks was not feasible due to the non-significance of the GLM. The model yielded (R^2 = 0.02, adj. R^2 = 0.000, $F(5, 210)$ = 0.843, p = 0.521), suggesting that the independent variables do not significantly predict changes in the SoA scores for joint tasks (cf. Figure 13). This lack of significance implies that there were no measurable effects of the experimental conditions on participants' sense of agency regarding joint tasks.

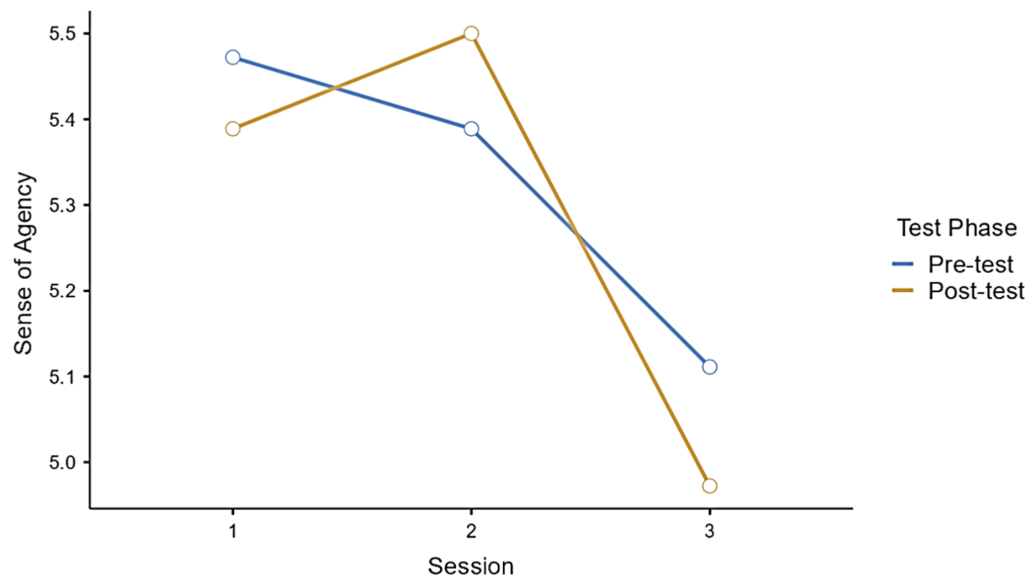

Figure 13. Changes in the sense of agency scores of the joint tasks at different sessions

Judgment of Performance (JoP) scores

The GLM for analyzing the changes in JoP scores for the solo tasks was not significant (R^2 = 0.03, adj. R^2 = 0.007, $F(5, 210)$ = 1.29, p = 0.269) (cf. Figure 14). This suggests that neurostimulation did not result in any statistically significant changes in JoP for the solo tasks, as the model explained only a small and non-significant portion of the variance in the post-test scores.

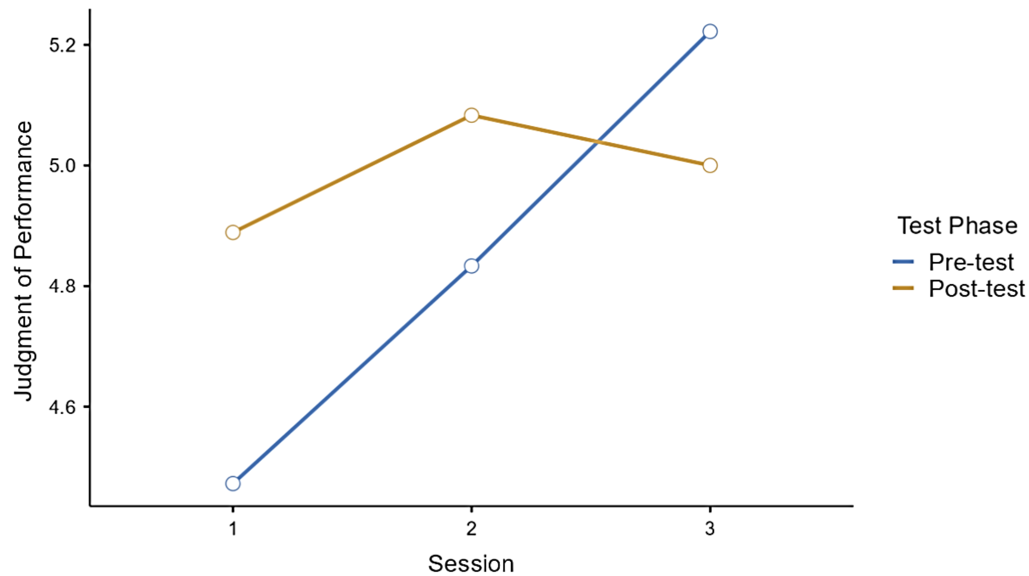

Figure 14. Changes in the judgment of performance scores of the solo tasks at different sessions

It is not possible to examine the changes in JoP scores for the joint tasks due to the non-significance of the model ($R^2 = 0.023$, adj. $R^2 = 0.000$, $F(5, 210) = 0.97$, $p = 0.437$) (cf. Figure 15). This indicates that the model failed to detect any significant effect or explain meaningful variance in the post-test JoP scores for the joint tasks.

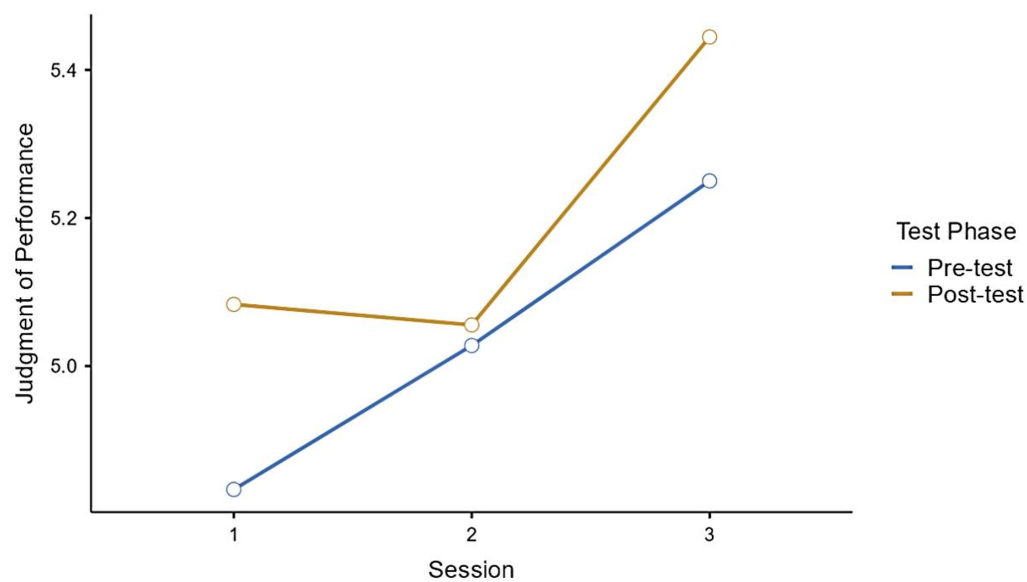

Figure 15. Changes in the judgment of performance scores of the joint tasks at different sessions

Performance (action time error and number of errors)

The GLM analysis demonstrated a strong and significant power to examine changes in action time error across all sessions ($R^2 = 0.045$, adj. $R^2 = 0.034$, $F(5, 426) = 4.04$, $p = 0.001$). This significance was attributed specifically to the effect of sessions ($F(2, 426) = 9.539$, $p < 0.001$), indicating that action time error varied significantly across different sessions (cf., Table 3). However, the analysis did not reveal any significant effects concerning the phases, suggesting that the phases did not contribute meaningfully to the variability in action time error scores.

Table 3. GLM for carryover effect on the action time error as dependent variable and sessions as factor

	SS	df	F	p
GLM model	317.386	5	4.041	0.001
Session	299.662	2	9.539	< .001
Test Phase	0.324	1	0.021	0.886
Session ✻ Test Phase	17.401	2	0.554	0.575
Residuals	6691.36	426		
Total	7008.746	431		

The intercept index of the GLM is 8.684 (95% CI [8.309, 9.059]). The changes observed between the first and second sessions yielded an estimate of -1.651 (95% CI [-2.569, -0.733], $t(426) = -3.536$, $p < 0.001$). Additionally, the changes between the first and third sessions showed an estimate of -1.863 (95% CI [-2.781, -0.945], $t(426) = -3.989$, $p < 0.001$) (cf., Table 4). These results indicate significant differences in action time error across sessions, with notable reductions from the first to both the second and third sessions.

Table 4. Effects of session and test phase on the carryover effect on the action time error

				95% Confidence Intervals					
Names	Effect	Estimate	SE	Lower	Upper	β	df	t	P
(Intercept)	(Intercept)	8.684	0.191	8.309	9.059	0	426	45.54	< .001
Session1	2 - 1	-1.651	0.467	-2.569	-0.733	-0.41	426	-3.536	< .001
Session2	3 - 1	-1.863	0.467	-2.781	-0.945	-0.46	426	-3.989	< .001
Test Phase1	Post-test - Pre-test	-0.055	0.381	-0.804	0.695	-0.01	426	-0.144	0.886
Session1 ✻ Test Phase1	(2 - 1) ✻ (Post-test - Pre-test)	0.415	0.934	-1.421	2.251	0.103	426	0.444	0.657
Session2 ✻ Test Phase1	(3 - 1) ✻ (Post-test - Pre-test)	0.979	0.934	-0.857	2.815	0.243	426	1.048	0.295

Among the results of the post-hoc tests, the most significant finding pertains to the changes in the amount of action time error during the pre-test phase between the first and third sessions. This comparison revealed notable negative changes, with a t-value of 3.5619 (p < 0.001, $p_{bonferroni}$ = 0.006). This indicates a significant reduction in action time error from the first session to the third session, highlighting a positive trend in performance over time (cf., Figure 16).

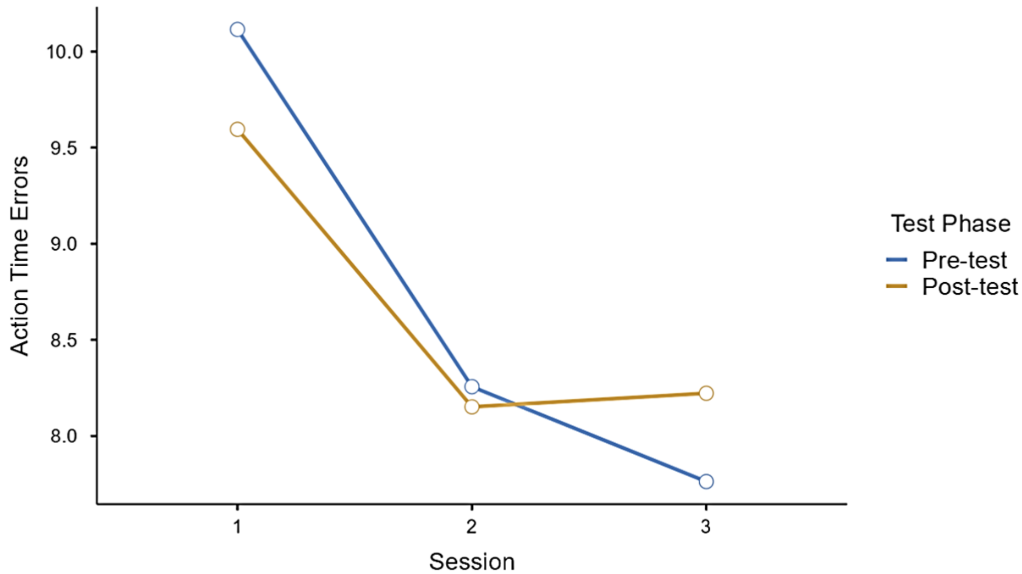

Figure 16. Changes in the action time error at different sessions

The GLM model demonstrates significant power in examining changes in the number of errors across all sessions, with (R^2 = 0.039, adj. R^2 = 0.024, $F(5, 318)$ = 2.57, p = 0.027). The analysis indicates that the effect of sessions is statistically significant, with ($F(2, 318)$ = 5.769, p = 0.003) (cf., Table 5). However, no significant effects were observed in relation to the phases of the tasks, suggesting that while session differences contribute to changes in error rates, the phases do not appear to have a notable impact.

Table 5. GLM for carryover effect on the number of errors as dependent variable and the sessions as factor

	SS	df	F	p
GLM model	153.395	5	2.569	0.027
Test Phase	11.864	1	0.993	0.32
Session	137.802	2	5.769	0.003
Test Phase ✻ Session	3.728	2	0.156	0.856
Residuals	3797.704	318		

Total	3951.099	323

The intercept index of the GLM model for the analysis of changes in the number of errors is calculated at 2.228 (95% CI [1.851, 2.606]). The changes observed between the first and second sessions are represented by an intercept of (95% CI [-2.018, -0.167], $t(318) = -2.323$, $p = 0.021$), resulting in a t-value of -1.556 (95% CI [-2.481, -0.63] $t(318) = -3.308$, $p = 0.001$), indicating statistical significance. Additionally, the changes between the first and third sessions show an intercept of (95% CI [-2.481, -0.630], yielding a t-value of $t(318) = -3.308$ and a p-value of 0.001 (cf., Table 6). This highlights significant negative changes in the number of errors between the first and second, and the first and third sessions, reinforcing the finding of increased performance over time.

Table 6. Effects of the session and test phase on the carryover effect on the number of errors

				95% Confidence Intervals					
Names	**Effect**	**Estimate**	**SE**	**Lower**	**Upper**	**Β**	**df**	**t**	**p**
(Intercept)	(Intercept)	2.228	0.192	1.851	2.606	0	318	11.607	< .001
Test Phase1	Post-test - Pre-test	0.383	0.384	-0.373	1.138	0.109	318	0.997	0.32
Session1	2 - 1	-1.093	0.47	-2.018	-0.167	-0.312	318	-2.323	0.021
Session2	3 - 1	-1.556	0.47	-2.481	-0.63	-0.445	318	-3.308	0.001
Test Phase1 ✻ Session1	(Post-test - Pre-test) ✻ (2 - 1)	-0.185	0.941	-2.036	1.665	-0.053	318	-0.197	0.844
Test Phase1 ✻ Session2	(Post-test - Pre-test) ✻ (3 - 1)	0.333	0.941	-1.517	2.184	0.095	318	0.354	0.723

Among the post-hoc test results, the only thing that is important for us and at the same time has a high significance is the changes in the number of errors in the pre-test stage of the first and third sessions, which also faced negative changes ($t(318) = 2.5895$), $p = 0.01$, $p_{bonferroni} = 0.151$) (cf., Figure 17).

Among the post-hoc test results, the key finding pertains to the changes in the number of errors during the pre-test stage between the first and third sessions. This change is notable for its high significance ($t(318)=2.5895$), $p = 0.01$, $p_{bonferroni} = 0.151$) indicating that while the change is significant, it may not reach the stringent criteria set by the Bonferroni correction. These results suggest a meaningful reduction in the number of errors from the first to the third session, highlighting improved performance over time. This finding is visually represented in Figure 17, illustrating the negative changes observed in the number of errors.

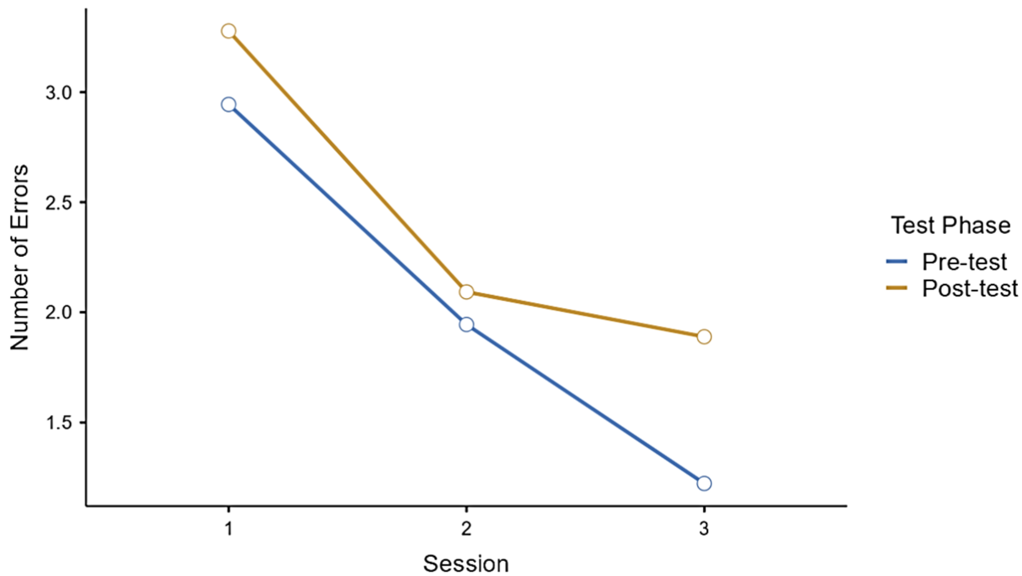

Figure 17. Changes in the number of errors at different sessions

Discussion

In the current research we aimed to understand whether the inhibitory rTMS of rTPJ using cTBS affects the quality of SoA, JoP, and the joint action performance. We further applied excitatory rTMS on the lAG to investigate the extent that iTBS neurostimulation affects the quality of SoA, JoP, and the joint action performance. Hypotheses of this research and its neurostimulations were designed based on the neuroimaging results of previous research that determined the role of these areas in monitoring SoA and matching action and result.

The statistical analysis of datasets shows the fact that none of the neurostimulation protocols in this research, either the inhibitory neurostimulation of the rTPJ, or the excitatory neurostimulation of lAG, do not significant effect on SoA, JoP and performance status. These results are also true for the sham intervention of the Vertex area whicd revealed the equality of the conditions of the real and pseudo-real neurostimulations (sham) of the experiment.

Comparing different sessions, data confirms the existence of a carryover effect on participants' performance. The negative changes in the action time error and the number of errors in the pre-test conditions, between the second sessions compared to the first sessions, and also between the third sessions compared to the first sessions, indicate the effects of the participants' learning and improving their performance and mastery over the tasks and test conditions during the sessions.

Regarding the correlation of the overall pre-test values of all neurostimulations, a weak positive correlation can be seen between the scores of SoA and JoP scores of the joint tasks. A weak negative correlation is observed between JoP scores of joint tasks with action time error and number of errors. A weak negative correlation is also observed between JoP scores of solo tasks and action time error. There is no significant correlation among the other variables. Therefore, as expected in all tasks, the less errors people make, the better they judge their performance. According to the above findings, it is clear that in joint tasks, they experience a greater sense of joint agency.

After the inhibitory neurostimulation of the rTPJ, a moderate negative correlation was seen between JoP scores of solo tasks and number of errors, which was not observed in the overall pre-test conditions, but all the correlations of other dependent variables were lost. Therefore, and according to the hypotheses of the research, it can be concluded that by inhibiting the activity of this area, the process of directing attention towards the external factor (the presence of the experimenter) -in solo tasks- is disturbed, and as its presence fades, people can make a better judgment of have their own performance. It is clear that this conclusion is only true for solo tasks, probably because with the neurostimulation in this area, the process of directing attention to the presence of an external agent is disrupted, and therefore JoP in joint tasks will face problems. Also, when participants are involved in a joint action, more neural networks are involved in monitoring and processing the social aspects of the action, so it is likely that to intervene in the process of attention orientation during joint action (joint tasks), neurostimulation in more areas and neural networks is needed.

After the excitatory neurostimulation of lAG, a moderate negative correlation between SoA scores and JoP scores of solo tasks emerges, which was not present in the overall pre-test condition. At the same time, the weak positive correlation that was observed between the scores of SoA and JoP scores of joint tasks is no longer seen. The weak negative correlation that existed in the pre-test conditions between the joint task JoP scores with action time error and number of errors remained stable and gained moderate strength. Therefore, the point that the above findings make clear is that by excitation the activity of this area, the accuracy of mismatch checking will probably improve, and in this way, people will have a better JoP, and therefore they will have a better distinction of responsibility and a clearer SoA.

After the sham intervention of the Vertex area, all the correlations that existed in the overall pre-test conditions of the experiments disappeared and no other significant correlation was seen between any of the dependent variables. We speculate that one of the reasons may justify the non-significance of the effects of neurostimulations on dependent variables is the appropriateness of the selected MNI coordinates of the areas of neurostimulations. During the research history of the subject, various tasks have been used in behavioral research, and due to the nature and diverse conditions of the tasks, different neural areas have been identified for their related functions, which may be located close to each other. For example, the coordinates of the average peak of neural activity of the target areas of this research are not fixed and different neural regions but close to each other have been identified: angular gyrus (Farrer and Frith, 2002; Farrer et al., 2003; 2008; Balslev et al., 2006; David et al., 2007; Decety and Lamm, 2007; Schnell et al., 2007; Kontaris et al., 2009; Spengler et al., 2009a; Nahab et al., 2010; Tsakiris et al., 2010; Yomogida et al., 2010), middle temporal gyrus (David et al., 2007; Schnell et al., 2007; Spengler et al., 2009a; 2009b; Miele et al., 2011; de Bézenac et al., 2016), the inferior parietal lobule (Agnew et al., 2008; Miele et al., 2011; de Bézenac et al., 2016), supramarginal gyrus (Balslev et al., 2006; Tsakiris et al., 2010) and middle and superior temporal gyrus and inferior parietal lobule (Zito et al., 2020b). Of course, the neurostimulation areas of the present study have an area of several square centimeters (Miele et al., 2011; Zito et al., 2020a) and the magnetic wave propagation pattern of the MCF-B70 butterfly coil used in the neurostimulations also has a focality of 5 square centimeters (Deng et al., 2013). In this way and considering that all the desired areas were identified with the Neuro-navigation system, the possibility that the selected neural areas were not subjected to neurostimulation seems rejected. Unless the function of the selected neural areas of the research has conditions different from the nature of the research tasks, and therefore the neurostimulations in the activity of those regions have not reflected the expected behavioral changes in the desired dependent variables.

One of the other reasons that can be involved in the lack of significant effects of neurostimulations on dependent variables is the hemispheric lateralization of the neural activity of the mentioned areas regarding related functions. Many studies have observed bilateral activity of these areas (Decety et al., 2002; Farrer and Frith, 2002; Balslev et al., 2006; David et al., 2007; Agnew et al., 2008; Farrer et al., 2008; Kontaris et al., 2009; Spengler et al., 2009a; Nahab et al., 2011; Miele et al., 2011; de Bézenac et al., 2016; Zito et al., 2020b). Some studies show a dominant activity of the right hemisphere (Farrer et al., 2003; Matsuzawa et al., 2005; Schnell et al., 2007; Spengler et al., 2009b; Tsakiris et al., 2010; Yomogida et al., 2010) and one study has determined the dominance of the left hemisphere (Chambon et al., 2012). As mentioned, most studies confirm the bilateral activity of these areas in the emergence of SoA (Zito et al., 2020b). Therefore, it is possible that despite the application of neurostimulations in one hemisphere, the opposite hemisphere will continue the relevant processes and to some extent compensate for the functional defect of the hemisphere subject to neurostimulation. Also, due to the laterality of the activity of these areas in some researches and tasks, there is a possibility that the function of the affected hemisphere is not in accordance with the nature of the research tasks. Therefore, in these cases, neurostimulation in the activity of one hemisphere does not reflect significant behavioral changes in the dependent variables of the current research, or they cannot be observed and evaluated by the research tasks.

Choosing the appropriate protocol for neurostimulations is another reason that may be involved in the ineffectiveness of all neurostimulations. The protocols that are widely used for rTMS in most researches are 50 Hz TBS protocols. However, modified protocols that have been used less frequently are those that generate 30 Hz triple pulses with a 6 Hz excitation pattern and are applied twice in session (with a specified interval, which is a very important variable interval) (Nyffeler et al., 2006). As a related example, in a study that examined the role of rPPC neural activity in SoA, the use of 30 Hz cTBS protocol with a 15-minute interval between re-applying the protocol had a significant effect (Zito et al., 2021). Another study has also shown a stronger effect of this 30 Hz protocol than its 50 Hz counterpart, although this effect is conditional on applying the neurostimulation again and with a 15-minute interval between them (Goldsworthy et al., 2012). This difference in the effectiveness of protocols can be related to the mechanism of synaptic plasticity consolidation. As animal research has shown, incidental stimuli received from the environment or other areas of the brain can cause spontaneous neural activity and eliminate the effects of synaptic changes (Zhou et al., 2003). The rTPJ is primarily responsible for processing attentional orienting processes and theory of mind (Decety and Lamm, 2007; Corbetta et al., 2008; Young et al., 2010; Mars et al., 2012). In this way, it seems logical that during all stages of the test sessions, this area is exposed to a variety of environmental stimuli (with a social quality) and the effects of synaptic changes caused by neurostimulations are eliminated due to the mechanism of synaptic plasticity. Therefore, choosing the standard cTBS 50 Hz protocol could be the reason for the ineffectiveness of the inhibitory neurostimulations of the rTPJ.

Another potential reason that can explain the lack of effectiveness of neurostimulations is determining the output intensity of the TMS device based on the resting motor threshold. Although there is no suitable method for determining the output intensity of the TMS to affect the non-motor cortex areas of the brain (Shambon et al., 2015), there is a possibility that the resting motor threshold does not reflect the appropriate output intensity to affect the non-motor cortex areas of the brain. Boroojerdi et al., 2002; Robertson et al., 2003; Oliver et al., 2009).

On the other hand, the nature of the research tasks may be a factor that does not reflect the quality of the sense of joint agency. The emergence of the sense of joint agency is dependent on several factors, but the factor that may have made the tasks of the present research into an inappropriate task with the goals of this research is the lack of action choice. The action choice is a vital aspect of people's agency that increases control (Wenke et al., 2010) and this freedom to choose action from among multiple options improves SoA (Krause, 2012; Chen, 2013). It has been determined that in situations where there are several options for action, but choosing each of the options has the same result (such as selecting a key from among several keys on the keyboard and receiving the same result), a greater SoA is experienced (Libet, 2002; Obhi and Hall, 2011). In the conditions of joint action, where the party responding to the action is also an independent agent with an agentic status, the action choice of one person leads to the unpredictable response of another person, and this event disrupts the causal relationship between the agent and the respondent, and this unpredictability, It questions the individual agency and therefore provides the context for the emergence of joint agency (Pfeiffer et al., 2012). The joint action of this research was the exact execution of a pre-defined drum-break, in which no changes were allowed and there was no action choice. Therefore, the nature of these tasks can be a reason for the invariability of the quality of SoA. Because it has created inflexible conditions that have made it very difficult for the flexibility of the resulting an agentic experience.

The long duration of the tasks is another issue that is thought-provoking. The length of the tasks causes excessive predictability and the loss of the basic feature of joint action, i.e. the continuous need for coordination and adaptation. Therefore, it is likely that participants ignore the responsibility of the other person in the joint action and do not feel joint agency. As we anticipated this issue from the beginning of the research, and in order to check it, we observed the behavior of the participants during the execution of the tasks in all sessions. In some cases, there were signs that indicated the monotony of the tasks and the boredom of the participants: facial expressions, occasional looking around by the participants, shaking of the legs that was not in sync with the music beats, and the apparent absence of signs of sensorimotor coordination, which probably indicate a lack of the feeling groove. These cases were only observed after a time, and before that, the behavior of participants was normal, or they even showed behaviors related to being involved in tasks and feeling groove. During the conversations that were held later with these participants, some of them confirmed the above-mentioned cases. Therefore, it seems that, at least for some participants, the long duration of the tasks created unfavorable conditions.

One of the notable issues was how the participants rated their SoA. In some cases, the recorded scores of some participants did not match the nature of the tasks. Naturally, it is expected that the scores of the participants' SoA in joint tasks, compared to solo tasks, tend towards a more social and joint quality, but sometimes this match was not seen. That is, the scores recorded in joint tasks were close to the scores of solo tasks, and apparently, performing the task alone or in pairs did not make a difference in the quality of people's SoA. According to the explanation of the participants, when the other party of the joint tasks (experimenter) had a perfect performance, they did not need any effort to correct the performance of the other party or to coordinate with it, and the only necessary task for which they tried was the correct implementation of their individual contribution in the joint tasks. Therefore, they did not have a different feeling than the feeling of agency caused in solo tasks.

Another very important issue was the way some participants rated their JoP. When the participants' actual performance differed greatly from their JoP scores, they were asked about the reason for this and how to evaluate and score. In most cases, their explanation was based on their different expectations of their ability and performance. In other words, when they performed well but submitted a bad score, their expectation was that they should perform better, and therefore they perceived their current performance as worse than their expected level of ability and underestimated their performance. On the contrary, when they submitted a good score but performed badly, they expected to perform worse, and therefore they considered their current ability level to be better than their expected performance and overestimated their performance. Moreover, in some cases, the participants stated that their scoring was affected by the experimenter's good performance (the opposite party of their joint action) and underestimated their performance. According to these interpretations, it seems that there is a certain bias in the way of JoP of the participants and scoring them, which was influenced by their expectation of the ratio of ability to their own performance as well as the experimenter's performance.

Limitation and suggestions

Limitations in participant recruitment, resulted in a final sample size of only eighteen individuals. This small sample size may have contributed to the observed lack of significant effects of neurostimulation on the targeted dependent variables. Additionally, the diversity of participants' musical skills and expertise presented another limitation. The sample comprised both musicians and non-musicians, and prior research has shown that the level of musical skill can influence the SoA (Pansardi et al., 2020). While participants were initially screened using the MBEA test to ensure they met minimum requirements for task performance, there remained a wide range of musical expertise (from zero to eighteen years of experience). Given the small number of volunteers, re-screening was not feasible, leading to a heterogeneous demographic condition that could act as a confounding variable. Future studies should aim to recruit participants with similar musical backgrounds to better control for these demographic factors.

In this research, each neural region was subjected to only one type of neurostimulation. To gain a more comprehensive understanding of the activity within these areas, future studies should consider applying both inhibitory neurostimulation to the lAG and excitatory neurostimulation to the rTPJ. Moreover, employing modified 30 Hz protocols may yield stronger effects and reveal different outcomes. We also recommend that future studies incorporate EEG measurements at multiple time points: as a baseline, during stimulation, and after stimulation. This multifaceted approach would allow researchers to capture real-time neural activity and provide a deeper understanding of the neural correlates associated with performance. By analyzing EEG data collected during the stimulation, it may be possible to identify immediate neural responses to the different types of neurostimulation and how these responses correlate with the observed behavioral outcomes. Furthermore, post-stimulation EEG measurements could help elucidate the enduring effects of rTMS on brain function. By comparing pre- and post-stimulation EEG readings, future researchers could assess how neurostimulation influences neuro-cognitive processes related to SoA and JoP over time. Finally, utilizing joint action tasks that incorporate a greater variety of action choices and unpredictable elements may create a more suitable environment for fostering a sense of joint agency among participants. Additionally, incorporating an electric drum instrument, played with specialized drumsticks, could enhance sensorimotor coordination and the feeling of groove, ultimately improving the sense of joint agency through increased freedom of movement.

Conclusion

The analysis of the data revealed no significant changes resulting from neurostimulation of the rTPJ and lAG on the scores for SoA, JoP, or performance metrics (action time error and number of errors) among participants. However, notable correlations among these variables suggest that neurostimulation may influence the interrelationships between them. These findings indicate that while direct effects of rTMS on SoA and JoP may not be evident, the underlying dynamics of how these constructs interact could be shaped by neurostimulation. Further research is warranted to explore these correlations and to understand the complexities of how neurostimulation impacts perceived agency and performance in coordinated joint actions.

Contributions

All authors contributed to the conceptualization of the study. **AJN** and **PF** are acknowledged as shared first authors of this paper. **PF**: methodology, investigation, data collection, data curation, original draft preparation, validation, formal analyses, data visualization, software, resources, project administration; **AJN**: methodology, investigation, data curation, original draft preparation, validation, formal analyses, data visualization, reviewing and editing, final revision, supervision; **RK**: supervision, methodology; **JH**: methodology, resources, funding acquisition, project administration; supervision.

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

Ethical approval

This study was approved by the research ethics committee of the Iranian Institute for Cognitive Science Studies (ICSS) (IR.UT.IRICSS.REC.1402.011).

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