Beat Perception in Cortical Motor Areas: An fNIRS Study

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ABSTRACT

Humans often respond to a rhythm by moving to the beat, indicating that the brain's motor regions may be involved in beat perception. A previous study investigating this theory using functional magnetic resonance imaging (fMRI) showed that listening to rhythms activated the supplementary motor areas (preSMA and SMA) and dorsal premotor cortex (PMd), while rhythms with a strong beat increased activation in the preSMA and SMA. fMRI adequately supported the scope of this experiment, but its restriction of bodily movement presents a considerable limitation for its general utility in this field. An alternative neuroimaging technique, functional near-infrared spectroscopy (fNIRS), can record superficial cortical activity while overcoming fMRI's movement restraint. It remains unclear how well fNIRS can be applied to the existing experimental paradigms in music neuroscience. The current study tested the feasibility of using fNIRS to replicate fMRI-based findings on beat perception in cortical motor regions. Participants were scanned while discriminating between simple auditory rhythms eliciting the feeling of either a strong beat, weak beat, or no beat. We predicted that preSMA, SMA, and PMd activation would be detected in response to all rhythms, while increased activity in the preSMA and SMA would be detected to rhythms with a strong beat. We found no significant changes to preSMA, SMA, or PMd activity in response to auditory rhythms when compared to rest. During the comparison of rhythms with strong beat to those with weak beat and no beat, we found no significant changes in SMA activity and a decrease in preSMA activity. Results were unable to confirm the capacity of fNIRS to reproduce fMRI measures of cortical activity using the existing paradigms, but experimental limitations provide an explanation for this outcome. These limitations ultimately substantiate our inability to support fNIRS as a promising tool for future investigations of motor regions' role in beat perception.

ACKNOWLEDGEMENTS

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I would like to express my greatest appreciation to my principal investigator, Dr. Jessica Grahn, for granting me the opportunity to conduct an experiment that aligned with my interests and for fostering a research environment that allowed me to thrive. I have been very lucky to be involved with the Grahn Lab in completing this project. Thank you to all of the members who provided me with constructive input in every step of this process, and for showing me what it is like to be part of a wonderful research team.

INTRODUCTION

Music is one of the most universal forms of human communication, spanning across the world's cultures. Notably, this expression is often accompanied by spontaneous movement. People seemingly have an intrinsic compulsion to move to a rhythm, whether it be a dramatic dance or a simple tapping of the foot. Studies investigating our motor response to rhythm point to music's temporally consistent pulse, or "beat," as an integral component underlying this phenomenon (Cooper et al., 1960; Large & Palmer, 2002). Experiments often evoke the feeling of a beat using evenly-spaced accented events (i.e., notes separated by regular intervals that are perceived as more salient than others) (Povel & Essens, 1985; Lerdahl & Jackendoff, 1996; Bouwer et al., 2018). While changes to pitch and volume often enhance accents' salience, an isochronous beat can arise even in the absence of alterations to sonic qualities (Brochard et al., 2003). This can be achieved by manipulating a rhythm's structure such that the onset of its notes are separated by regular, integer ratio intervals (Povel & Okkerman, 1981; Sakai et al., 1999). For example, tone onsets separated by 250, 500, and 1000 milliseconds (ms) have a 1:2:4 interval relationship. The "1" interval represents a single unit, and perceptual accents can be elicited when tones are arranged into groups equal to four units in length (Povel & Essens, 1985). Rhythms containing noninteger ratio intervals (e.g., 1:2.4:3.8) cannot be partitioned into interval groupings of equal length and are thus unable to maintain this same consistent pulse.

To investigate the processing of beat in the brain's motor regions, Grahn & Brett (2007) constructed three stimulus categories: (1) a strong beat condition using integer ratio intervals with evenly-spaced perceptual accents; (2) a weak beat condition with integer ratio intervals rearranged to induce irregular accents; and (3) a no beat condition using noninteger ratio

intervals evoking no perceptible beat.[1] During functional magnetic resonance imaging (fMRI) scanning, 27 participants were tasked with identifying whether auditory rhythms were identical or distinct. Within each trial, a sequence of auditory tones (either of strong, weak, or no beat) was presented twice. This was followed by a third presentation of a sequence within the same experimental condition, which was either identical to the first presentations or a slightly altered sequence. All three rhythmic conditions elicited activation in the brain's motor regions, including the supplementary motor areas (preSMA and SMA), dorsal premotor cortex (PMd), basal ganglia, and cerebellum. The Strong Beat condition particularly evoked greater activity in the basal ganglia, preSMA, and SMA when compared to the weak beat and no beat conditions. Even in the complete absence of movement, the brain's bilateral motor network had been activated by a regular beat.

Subsequent research has used fMRI to further explore the role of the motor system in beat perception. Most notably, the neuroimaging technique has emphasized the importance of this system's interactions with subcortical and auditory regions (Nguyen et al., 2018). fMRI-based findings illustrate the increased coupling of activity between the basal ganglia, supplementary motor area, premotor cortex, and superior temporal gyrus during beat perception (Grahn & Rowe, 2009; Kung et al., 2013). Musical training has also been shown to correlate with greater coupling in these regions (Chen et al., 2008; Grahn & Rowe, 2009). The empirical understanding of beat processing in motor areas continues to be informed by fMRI, but the technique bears significant limitations within this field. Here we outline the advantages of functional near-infrared spectroscopy (fNIRS) over fMRI in music neuroscience, and

[1] Conditions were originally labeled metric simple, metric complex, and non-metric by Grahn & Brett (2007). For reasons of maintaining simplicity, the current study will exclude the concept of metricism and will refer to these conditions as strong beat, weak beat, and no beat respectively.

subsequently characterize our partial replication of Grahn & Brett (2007) as an assessment of fNIRS' capacities in this field.

fNIRS is an optical imaging technique comparable to fMRI in that it measures real-time hemodynamics within the brain. It does so by exploiting the differences in absorption spectra of oxygenated and deoxygenated hemoglobin (Johannsen, 2018). Through a detection of changes in blood oxygen content, fNIRS indirectly monitors cellular metabolism to localize regions of neural activity (Ferrari & Quaresima, 2012; Guérin et al., 2021). Although fMRI and fNIRS are similar in their neurophysiological measurement, the imaging apparatuses differ drastically. fMRI is a stationary, bulky machine restricting those it scans to a static supine position (Scarapicchia et al., 2017). Conversely, the fNIRS apparatus makes use of optodes implanted into a cap fitted on an individual's head (Johannsen, 2018). It is through this experimental setup that the advantages of fNIRS arise over its more prominent counterpart.

fNIRS' most clear benefits are seen in its cost and portability. The equipment is significantly cheaper than fMRI (Cui et al., 2011; Liu et al., 2015) and can easily be transported across locations (Wagner et al., 2021). This makes fNIRS well-suited for clinical applications where patient transportation may be unfeasible or potentially harmful. However, the technology's greatest asset lies within its permission of movement while scanning. While fMRI is sensitive to even minimal motion (Scarapicchia et al., 2017), fNIRS has a comparatively robust tolerance to motion artifacts (Herold et al., 2018; Guérin et al., 2021). This is of particular importance within the realm of music neuroscience. Preliminary studies adopting fNIRS have been able to naturalistically target motor paradigms that would otherwise be exceedingly difficult to investigate. Examples include imaging the brain while playing instruments (Vanzella et al., 2019), walking to auditory cues (Vitorio et al., 2018), or dancing to music (Tachibana et al.,

2011; Ono et al., 2014). With a myriad of phenomena connecting human musical perception to movement, it is essential that fNIRS be utilized as a principal method of investigation in this field. Before the imaging technique is incorporated ubiquitously, however, its ability to be applied to the simple paradigms of beat perception must first be confirmed.

The present study seeks to assess fNIRS' applicability to the current experimental paradigms of beat perception by replicating the findings of Grahn & Brett (2007). This will be achieved by employing an identical rhythmic discrimination task during fNIRS scanning (rather than during fMRI scanning). It is predicted that this neuroimaging technique will replicate the results of the original paper within superficial cortical regions. However, due to fNIRS' diminished signal strength in deep biological tissue (Del Bianco, 2002; Hoshi, 2005; Cui et al., 2011), we do not expect to replicate observations of subcortical activity. We therefore hypothesize that fNIRS will detect higher activation in the preSMA, SMA, and PMd during all rhythms compared to rest, and will also find an increase in preSMA and SMA activation during rhythms with strong beat compared to those with weak beat or no beat. These findings would reflect fNIRS' suitability for application to existing experimental paradigms, and would support its integration into beat perception research. More broadly, the expected results would provide a preliminary indication that fNIRS may be incorporated into the broader field of music neuroscience, thereby permitting the exploration of ecologically valid avenues of research using a cheaper, more accessible imaging method.

METHODS

Participants

Thirteen participants (6 females, 7 males) were recruited after obtaining informed written consent to the experimental protocol, as approved by the Western Health Sciences Research

Ethics Board. All subjects were undergraduate students at London, Ontario's Western University, ranging from 20-23 years of age (M = 21.3, SD = 0.72). Seven of the participants had formal musical training with a range of 5-17 years (M = 9.9, SD = 4.05), six of whom were currently practicing. Eight of the participants were not musically trained. No other exclusion criteria were used.

Stimuli

Ninety auditory rhythmic sequences, composed from sets of five, six, or seven tone intervals were created based on previous work (Grahn & Brett, 2007). These sequences were divided evenly between three experimental conditions: strong beat, weak beat, and no beat. The strong beat condition was composed of intervals related by integer ratios. Importantly, these intervals were arranged such that regular perceptual accents (Povel & Essens, 1985) were induced every four units (Figure 1). For every strong beat stimulus, an associated weak beat condition was constructed using identical integer ratio intervals. However, these intervals were rearranged to induce inconsistent groupings of auditory tones, leading to irregular perceptual accents and a diminished beat salience. Finally, the no beat condition was constructed from the Weak Beat stimuli, but instead contained noninteger ratio intervals related by divisions of 1:1.4:3.5:4.5. That is, interval lengths with a ratio of 2 were changed to 1.4, those of 3 to 3.5, and those of 4 to 4.5. Because this condition possessed both temporally inconsistent intervals and groupings, no beat would be maintained from its sequences. In addition to these three conditions, silent null trials were sparsely administered to collect baseline data. These ten-second silent intervals were presented at an approximate frequency of once every 15 trials.

To control for differences in tempo, the value of the "1" interval within each rhythmic sequence was randomly chosen between 220-270 ms in 10 ms steps. The remaining interval

values were thus altered based on this assignment. For example, if the strong beat stimulus portrayed by Figure 1 was assigned a "1" interval value of 250 ms it would be composed of tones with length 500, 500, 250, 750, 750, and 250 ms sequentially. Aside from a 40 ms gap to indicate the end of one tone and the beginning of the next, tones lasted the duration of the interval. All tones were played at a frequency of 441 Hz. Table 1 displays the complete list of rhythmic sequences used, exactly matching those used in the study we sought to replicate.

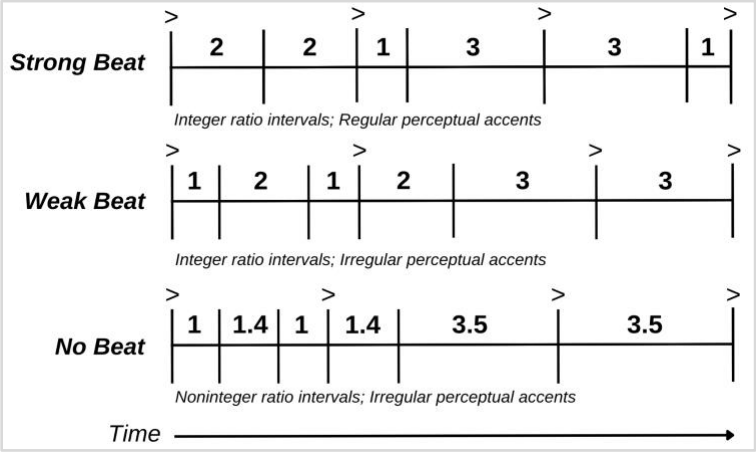

Figure 1. Sample Stimuli Schematic. Vertical bars represent tone onsets and ">" represents a perceptual accent. Onsets within the strong beat stimulus are rearranged to construct the weak beat stimulus. Integer ratio intervals within the weak beat stimulus are converted to noninteger ratio intervals to construct the no beat stimulus. Adapted with permission from Grahn & Brett (2007).

For every sequence displayed in Table 1, a corresponding deviant stimulus was constructed. This was achieved by dividing one interval in the original sequence into two separate intervals, and combining two separate intervals in the original sequence into one. For example, the deviant sequence to 311322 was constructed as 314112, with the 13 becoming 4 and the first 2 becoming 11. Using this strategy, deviant sequences could be assembled that maintained the number of intervals and did not alter the condition type (i.e., there were no trials

with cross-condition comparisons where the deviant stimulus was of a different category than the first sequence).

Table 1. Complete List of Rhythmic Sequences.

	Strong Beat	*Weak Beat*	*No Beat*
5 Intervals	2 2 4 1 3	1 3 2 4 2	1 3.5 1.4 4.5 1.4
	3 1 4 1 3	1 1 3 4 3	1 1 3.5 4.5 3.5
	3 1 4 2 2	2 1 3 2 4	1.4 1 3.5 1.4 4.5
	4 1 3 3 1	3 3 1 4 1	3.5 3.5 1 4.5 1
	4 3 1 1 3	4 1 1 3 3	4.5 1 1 3.5 3.5
	4 3 1 2 2	4 1 2 3 2	4.5 1 1.4 3.5 1.4
6 Intervals	1 1 2 3 1 4	1 2 4 1 1 3	1 1.4 4.5 1 1 3.5
	1 1 2 4 2 2	1 2 2 1 4 2	1 1.4 1.4 1 4.5 1.4
	2 1 1 1 3 4	2 1 4 3 1 1	1.4 1 4.5 3.5 1 1
	2 1 1 2 2 4	2 1 4 2 2 1	1.4 1 4.5 1.4 1.4 1
	2 1 1 4 1 3	2 1 4 2 2 1	1.4 1 4.5 1.4 1.4 1
	2 2 1 3 3 1	1 2 1 2 3 3	1 1.4 1 1.4 3.5 3.5
	2 2 2 1 1 4	2 2 1 2 4 1	1.4 1.4 1 1.4 4.5 1
	2 2 3 1 1 3	2 3 1 1 2 3	1.4 3.5 1 1 1.4 3.5
	3 1 1 3 2 2	1 3 2 3 2 1	1 3.5 1.4 3.5 1.4 1
	3 1 2 2 1 3	3 2 3 2 1 1	3.5 1.4 3.5 1.4 1 1
	4 1 1 2 3 1	4 2 1 3 1 1	4.5 1.4 1 3.5 1 1
	4 2 2 1 1 2	4 1 2 2 1 2	4.5 1 1.4 1.4 1 1.4
7 Intervals	1 1 1 1 4 3 1	1 3 1 4 1 1 1	1 3.5 1 4.5 1 1 1
	1 1 2 2 1 1 4	1 1 1 2 4 1 2	1 1 1 1.4 4.5 1 1.4
	1 1 2 3 1 1 3	1 1 3 2 1 3 1	1 1 3.5 1.4 1 3.5 1
	1 1 2 3 1 2 2	1 1 3 2 2 1 2	1 1 3.5 1.4 1.4 1 1.4
	2 1 1 2 2 3 1	2 1 2 3 2 1 1	1.4 1 1.4 3.5 1.4 1 1
	2 1 1 3 1 1 3	2 3 3 1 1 1 1	1.4 3.5 3.5 1 1 1 1
	2 2 1 1 1 1 4	2 1 4 1 2 1 1	1.4 1 4.5 1 1.4 1 1
	3 1 2 1 1 1 3	3 1 1 3 1 2 1	3.5 1 1 3.5 1 1.4 1
	3 1 2 2 1 1 2	3 2 2 1 1 1 2	3.5 1.4 1.4 1 1 1 1.4
	3 1 4 1 1 1 1	3 1 1 4 1 1 1	3.5 1 1 4.5 1 1 1
	4 1 1 1 1 3 1	1 4 1 1 3 1 1	1 4.5 1 1 3.5 1 1
	4 2 2 1 1 1 1	4 1 1 1 2 2 1	4.5 1 1 1 1.4 1.4 1

30 sequences were constructed for each rhythmic condition. Sequence tempo was randomized such that “1” represents an interval value between 220 and 270 ms (increasing in 10 ms incremental steps). The remaining intervals in each sequence are multiplied by the length assigned to the 1 interval to determine their duration. Adapted with permission from Grahn & Brett (2007).

Task

During fNIRS scanning, subjects were tasked with discriminating between rhythmic sequences played from the speakers of a Dell Precision M4800 computer. In each trial an auditory sequence of tones was presented twice, followed by a single presentation of a second sequence that could be the same or deviant from the first (Figure 2). Deviant stimuli were presented in 50% of trials. Participants pressed the computer's 'F' key to indicate that they heard the third presentation as being identical to the first two and the 'J' key to indicate that they heard the third as different. Sequence lengths varied between trials based on tempo randomization, but within each trial all three rhythm presentations equated in tempo and length. Regardless of subjects' reaction time in responding, the experiment continued to the next trial after a five-second response window. Behavioural data was analyzed based on the proportion of correct responses for each of the three conditions (strong, weak, and no beat).

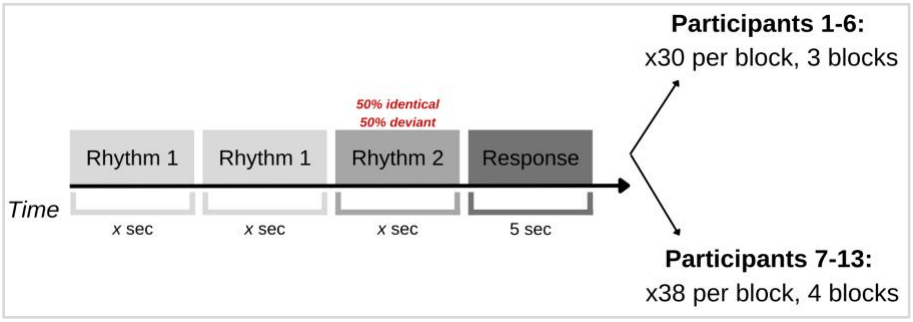

Figure 2. Rhythm Discrimination Task. Participants were presented a first sequence (Rhythm 1) twice, followed either by the same or a deviant sequence (Rhythm 2) with equal probability between the two options. Rhythm lengths (*x*) depended on the tempo assigned to the condition, while the response window remained a uniform length of 5 seconds. Participants 1-6 were administered a different number of trials and blocks than participants 7-13.

Grahn & Brett (2007) scanned participants for a total of four blocks, each consisting of 38 trials. This constituted a 40-minute procedure in total. Unfortunately, due to experimental error, this session was shortened to three blocks of 30 trials for the first six participants of the

present study (Figure 2). This reduced the testing period to approximately 30 minutes. For the final seven participants, however, a full 40-minute replication of the original experiment's four 38-trial blocks was conducted. Aside from their keyboard responses, all thirteen participants were instructed to remain as still as possible throughout the testing procedure.

fNIRS

The present experiment used a wearable fNIRS device (NIRSport™, NIRX, Germany) optimized for mobile settings. The apparatus consisted of light emitting diodes (i.e., sources) projecting dual-wavelength light of 760 and 850 nm, photo-electrical detectors for light retrieval, and a signal amplifier. All long-distance optodes were secured by spring-loaded grommets. Short-distance detectors were placed underneath the fNIRS cap directly on participants' heads at locations equivalent to the long-distance detectors.

Participants' heads were measured prior to the scanning procedure. Circumference in the horizontal plane dictated which cap each subject received (either 54, 56, or 58 cm). Two measurements were then taken to correct cap positioning, both using Cz as the primary point of reference. Cz is often used in studies employing cap-based neuroimaging procedures as it indicates the cap's center-point on top of the skull (Klem et al., 1999). First, the distance between the nasion and inion was taken and the cap was adjusted to align Cz at the sagittal midpoint. The distance between the left and right periauricles was then taken and the cap was adjusted to align Cz at the coronal midpoint. Before assembling the channel apparatus, hair laying beneath optode locations was cleared to optimize signal quality.

Eight sources and seven detectors were arranged in a 8x7 motor montage based on the International 10-20 coordinate system (Klem et al., 1999) (Figure 3). An eighth detector was removed from the montage and was instead used to collect physiological data from all short-

distance channels. Optode distance ranged from 3 to 4 centimetres and sampling occurred at a rate of 10 Hz. Signal quality was assessed through an fNIRS data recording software (Aurora^{TM}) and alterations were carried out as needed prior to data collection.

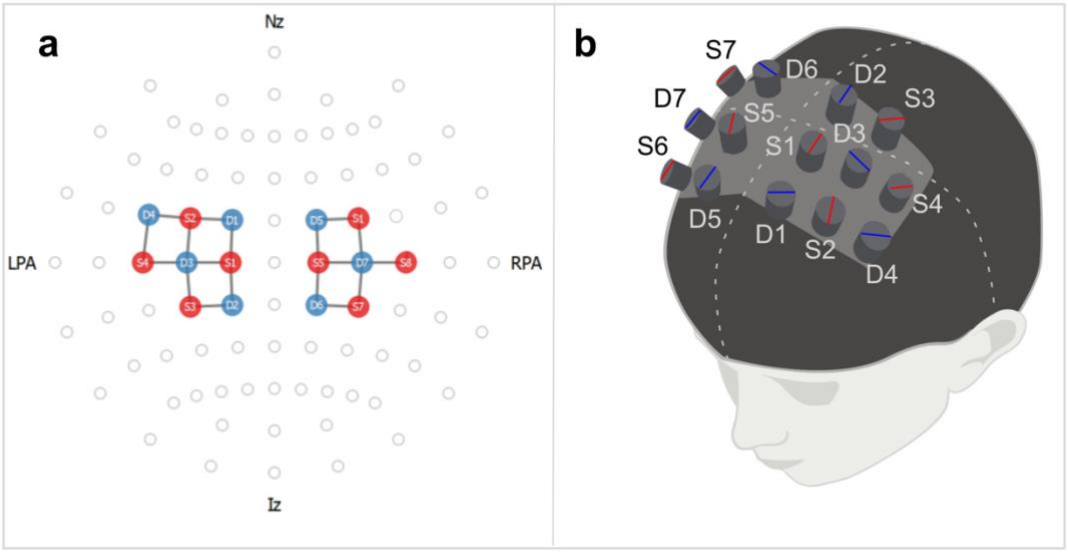

Figure 3. fNIRS Motor Montage. (**a**) Optode placement mapped onto the International 10-20 coordinate system. Taking a bird's-eye-view, the front of the head is located at the top of the schematic (Nz = nasion) and the back of the head is located at the bottom (Iz = inion). Sources (red) emit light that is received by adjacent detectors (blue) as indicated by grey gridlines. Bilateral asymmetry is due to the removal of Detector 8 for short-distance channel data collection. (**b**) Optode placement as it appeared on subjects' heads. Grey shaded region indicates the cortical motor area covered by the montage. Image reconstruction from Hramov et al., 2020.

Analysis

Raw fNIRS data was converted to optical density signals before undergoing three primary steps of data processing: (1) motion correction, (2) signal conversion and prewhitening, and (3) statistical analysis.

Motion correction was divided into two processes: spline interpolation and wavelet filtering. Spline interpolation was used to detect and diminish motion artifacts represented by slow signal drift and lasting baseline shifts. While this process was conducted using Homer3

(Huppert et al., 2009), all remaining steps of data processing were performed within the NIRS Brain AnalyzIR toolbox (Santosa et al., 2018). Unlike spline interpolation, wavelet filtering is effective for spikes and brief motion artifacts. It was implemented to identify outlier wavelet components and reconstruct the signal having made these exclusions. Because signal quality varied between subjects, different filtering thresholds were adopted to optimize the removal of motion without jeopardizing signal quality (interquartile ranges spanned from 0.15 – 0.8).

The 10 Hz signal was down-sampled to 4 Hz to permit the conversion from optical density to oxygenated and deoxygenated hemoglobin signals (i.e., negatively correlated signals represented by HbO and HbR, respectively). This conversion was achieved using the modified Beer-Lambert law and a standard partial pathlength factor of 0.1. Prewhitening at a length of ten seconds was subsequently conducted to remove serial autocorrelations due to delayed slow drift or physiological noise.

Two levels of statistics were then applied to the data. A general linear model was used to independently compare HbO and HbR results to template hemodynamic response functions. This method included a number of regressors of no interest, including data from all short-distance channels. A second level of statistics was performed through a linear regression model including only fixed effects. Fixed (rather than mixed or random) effects were used to enhance the statistical power of the current results.

To decipher how the processed data reflected varying activity in distinct neural regions, we defined our regions of interest (ROIs) using a large-scale meta-analytic database of Montreal Neurological Institute (MNI) based coordinates (Neurosynth^{TM}). The platform integrates data from thousands of neuroimaging studies to identify highly probabilistic locations of individual neural regions in MNI space. By applying this information to the International 10-20 coordinate

system, we deduced the weighted average of source-detector channels that best represented the activity in each ROI. ROIs included the aforementioned preSMA, SMA, and PMd along with the primary motor cortex (M1) and ventral premotor cortex (PMv).

When making between-conditions comparisons of neural activity, all analyses were performed using the GLM beta-weights obtained from brain activity during the first two rhythmic presentations within each trial. Like Grahn & Brett (2007, p. 899), these presentations were isolated "to exclude activation due to deviant detection, decision making, and response preparation during the third rhythm presentation, and motor activation during the subsequent response."

RESULTS

Discrimination Results

Assessment of behavioural performance was conducted for two central reasons. We first sought to confirm that our employment of the auditory stimuli evoked a discrimination performance similar to that found by Grahn & Brett (2007). Additionally, like the original study, we also wanted to ensure that difficulty confounds were not eliciting significant effects (i.e., differences in activation between conditions was exclusively due to beat processing). A one-way ANOVA indicated that there were no significant differences between behavioural performance on the experimental conditions (F (2,10) = 3.18, p = 0.06) (Figure 4a). Percent of correct trials for each condition was 81% for strong beat (SD = 4.52), 81% for weak beat (SD = 5.04), and 87% for no beat (SD = 2.32). Visual inspection of the primary study's discrimination result indicated that our rates of correct discrimination generally matched those of Grahn & Brett (2007) (Figure 4b).

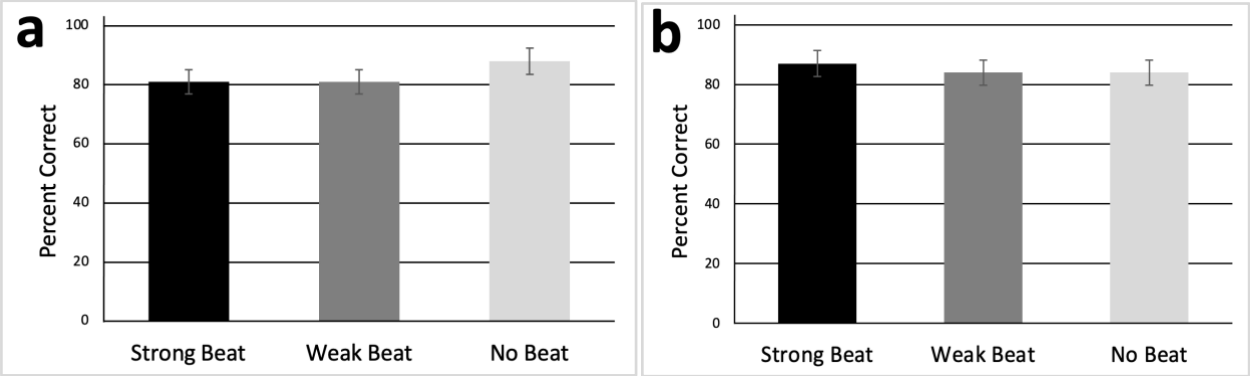

Figure 4. Discrimination Result. (**a**) The graph represents the percentage of trials correctly guessed by subjects across the three rhythmic conditions. There were no significant differences between conditions (p = 0.06). (**b**) A graph reconstructed from Grahn & Brett (2007) displaying visually similar results to the behavioural data collected in the present study.

Functional Imaging Results

Each ROI was defined and mapped in relation to the 8x7 fNIRS motor montage as seen in Figure 5. It was through this operationalization that measured cortical activity could be attributed to the corresponding neural area.

Between-conditions comparisons yielded mixed results. HbO and HbR analyses of all rhythms – rest showed no significant differences across ROIs (Figure 6a), but a strong beat – weak & no beat comparison yielded significant findings in both the HbO and HbR analyses. HbO responses were significantly lower in the preSMA during the strong beat condition ($t(12)$ = -2.16, p = 0.037). Conversely, HbO responses were significantly greater in the right M1 during the strong beat condition when compared to weak & no beat ($t(12)$ = 2.33, p = 0.025) while the HbR response in this region was significantly diminished ($t(12)$ = -3.02, p = 0.005) (Figure 6b).

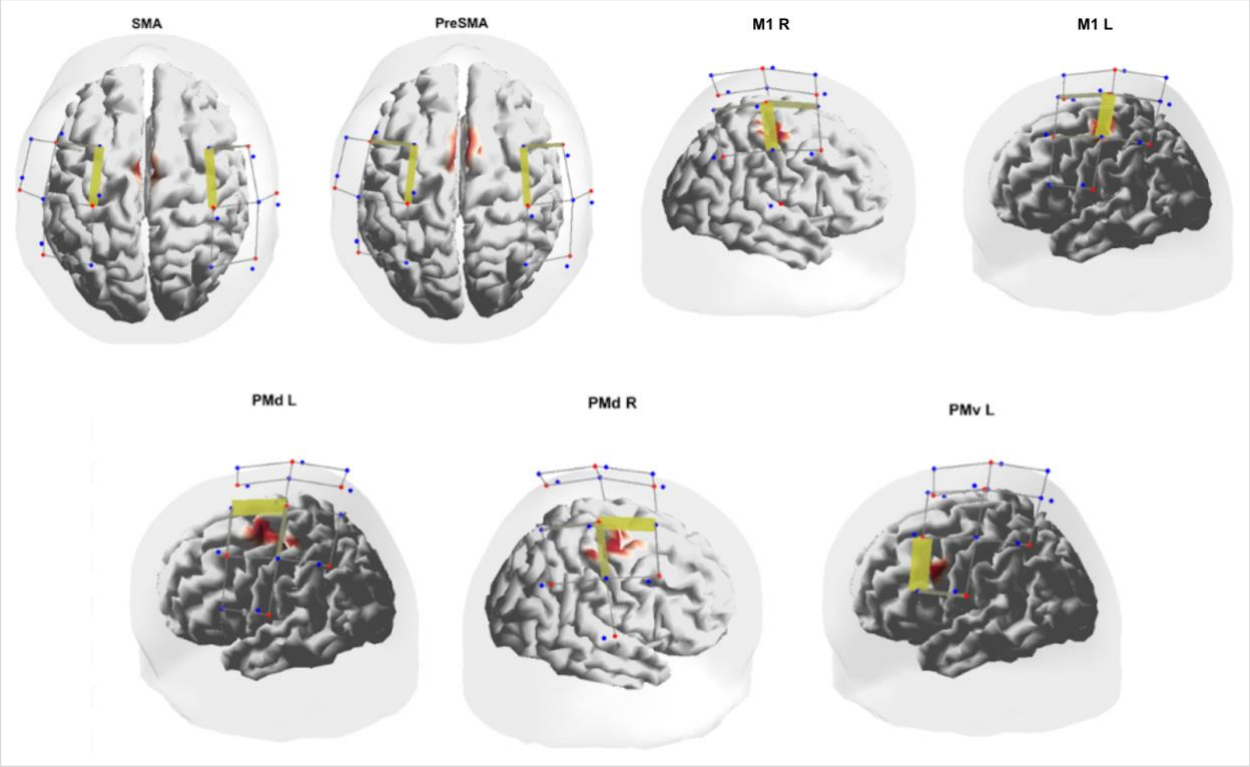

Figure 5. Region of Interest Localization. Shows the relationship between brain regions localized in MNI space and the 8x7 fNIRS motor montage employed. Shaded red regions represent ROIs and yellow line thickness indicates the extent to which the source-detector channel was weighted in detecting the region's activity. Right PMv could not be detected due to the absence of detector 8.

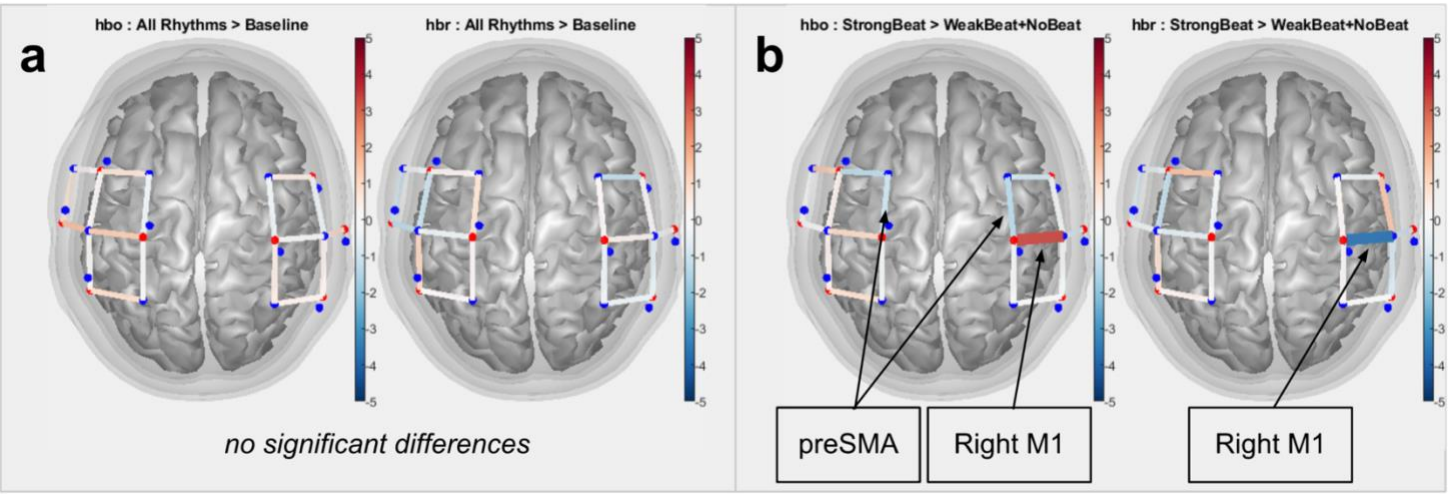

Figure 6. Imaging Results. Displays the HbO and HbR analyses used to compare brain activation between different combinations of conditions. Colour gradients signify *t*-values. Red gridlines represent source-detector channels that detected greater activity and blue gridlines represent source-detector channels that detected diminished activity. (**a**) Comparison of all rhythms – baseline. No significant differences in ROIs were found. (**b**) Comparison of strong beat – weak beat & no beat. Based on ROI localization, arrows indicate the primary source-detector channels used to infer preSMA and right M1 activity. HbO analyses found increased right M1 activity ($p = 0.025$) and decreased preSMA activity ($p = 0.037$) to rhythms with strong beat. HbR analyses found decreased right M1 activity ($p = 0.005$) to rhythms with strong beat.

DISCUSSION

Auditory rhythms have been shown to activate the brain's cortical motor regions particularly when associated with a salient beat. In this experiment, we sought to utilize this established finding as a means of assessing fNIRS' capacity to accurately measure motor regions' role in beat perception using paradigms currently existing in the literature. It was predicted that fNIRS would display this ability by replicating the findings of Grahn & Brett (2007), detecting an increase in preSMA, SMA, and PMd activity during auditory rhythm presentation, and elevated preSMA and SMA activity during rhythms with strong beat. Results did not support these hypotheses. A comparison of all rhythmic presentations to silence showed no significant changes in motor area activation, and a comparison of rhythms with a strong beat

to those lacking a strong beat did not alter the detected SMA activity. Furthermore, we detected a decrease in preSMA activity during rhythms with a strong beat. Our employment of fNIRS did not successfully replicate the findings of Grahn & Brett (2007), but this result appears to be primarily explained by experimental error rather than by limitations of the neuroimaging technology itself. We will qualify this conclusion by assessing the errors in our replication design and in our employment of fNIRS that may have produced our obtained results. This will provide an informed approach in the subsequent comparison of our findings with the broader literature.

Replication Design

The current study relied significantly upon successfully replicating the methods of Grahn & Brett (2007), making this an important factor to consider when examining our potential means of experimental error. The two methodologies displayed a number of similarities. For example, we used identical auditory sequences within each condition, induced deviance indistinguishably, and played our auditory sequences at equal tempos. Each of these factors was important in accurately replicating the original study's stimuli. The sample groups also matched on musicianship (each with an approximate 1:1 ratio of musicians to non-musicians), diminishing any potential confounds of expertise.

There were two minor differences between the studies' rhythm presentations. The primary experiment used stimuli that were randomized across six auditory frequencies (ranging from 284-597 Hz) while the current experiment held a constant frequency of 441 Hz. This randomization was performed by Grahn & Brett (2007, p. 895) to "cue subjects to each new trial," but time constraints led us to omit this detail and we had no reason to believe that it would alter subjects' beat perception or motor area activity. The second difference was the proportion

of deviant stimulus presentations. Deviant stimuli were only applied to 39% of trials in the original experiment, but no rationale was provided for this proportion. We believed that implementing a more conventional dual-response discrimination paradigm would best optimize our results, leading us to adopt an equal distribution of 50% identical and 50% deviant stimulus responses. Our behavioural results ultimately confirm that these alterations did not markedly differentiate our employment of the stimuli from Grahn & Brett (2007).

There were two significant differences between our replication design and the original experiment that impacted our results most. First, the present study had a substantially reduced quantity of data compared to Grahn & Brett (2007). This was primarily due to our total of 13 subjects, which provided sufficiently less data than the 27 participants of the original experiment. The effect of our sample size was compounded by the fact that our first six participants were only subjected to three blocks of 30 trials compared to the original study's four blocks of 38 trials. The diminished quantity of available data was thus a notable influence on our inability to achieve significant results.

The second major difference was our diminished quantity of null trials. The primary study split their trials evenly between strong beat, weak beat, no beat, and silent null conditions. While silent conditions were administered at an approximate rate of once per 15 rhythmic trials, a collection of baseline data before the testing procedure, between blocks, and after the testing procedure was believed to mitigate the need for an even inclusion of silent trials amongst the three experimental conditions. With fewer participants than Grahn & Brett (2007), our reduced quantity of null trials was performed to maximize the quantity of experimental data. However, difficulties in motion correction within baseline data jeopardized signal quality, forcing us to omit much of the baseline activity collected. Our method of spline interpolation has been shown

to present significant shortcomings when applied to substantial motion artifacts (Barker et al., 2013). Specifically, this method has been found to introduce undesirable baseline shifts that may not be detected by visual inspection (Jahani et al., 2018). Spline interpolation is also prone to overfitting its values, leading to a loss of information in its detected cortical activity (Barker et al., 2013; von Lühmann et al., 2020). These limitations not only restricted our quantity of usable baseline data, but also diminished the quality of the baseline activity used in analysis.

Employment of fNIRS

fNIRS is regularly employed to measure activity in cortical motor regions (Leff et al., 2011), specifically in the preSMA, SMA, and PMd (Suzuki et al., 2008; Wilson et al., 2014; Hramov et al., 2020; Klein et al., 2022). However, these experiments rarely use the 8x7 motor montage adopted in the present study. The montage was selected due to its establishment in the literature (Batula et al., 2017; Hramov et al., 2020), but further inspection shows that these experiments generally employ this optode configuration to make broad inferences of motor region activity. Our 8x7 arrangement displayed poor sensitivity to our ROIs as a result of two central issues. The configuration first suffered from poor optode placement, which particularly impacted the detected preSMA and SMA activity. Relative to these regions, the source-detector channels that most optimally measured preSMA and SMA activity were placed far too laterally on the scalp (Figure 7a). Other studies examining activity in supplementary motor areas avoid this issue by using channels that either run directly along the medial longitudinal fissure (Koenraadt et al., 2014; Nemani et al., 2018) or cross it transversely (Saleh et al., 2018). A study even adopting a simple 3x2 fNIRS montage effectively measured activity in supplementary motor areas (Koenraadt et al., 2014). It is clear that our detection of preSMA and SMA activity would have benefited from a more effective placement of our fNIRS optodes.

The second issue with our chosen 8x7 montage was its optode density. Due to the sparsity of sources and detectors, we were forced to infer the activity of distinct ROIs using similar channel combinations. This error was particularly apparent when comparing the channels used to detect activity in the right PMd versus the right M1 (Figure 7b). The source-detector channels used to infer activity from these two regions were almost identical, making it difficult to isolate the distinct activities of these two regions. More successful montages have made use of densely localized optode configurations above the different motor cortices to better differentiate between their respective activity (Nemani et al., 2018; Saleh et al., 2018; Klein et al., 2022).

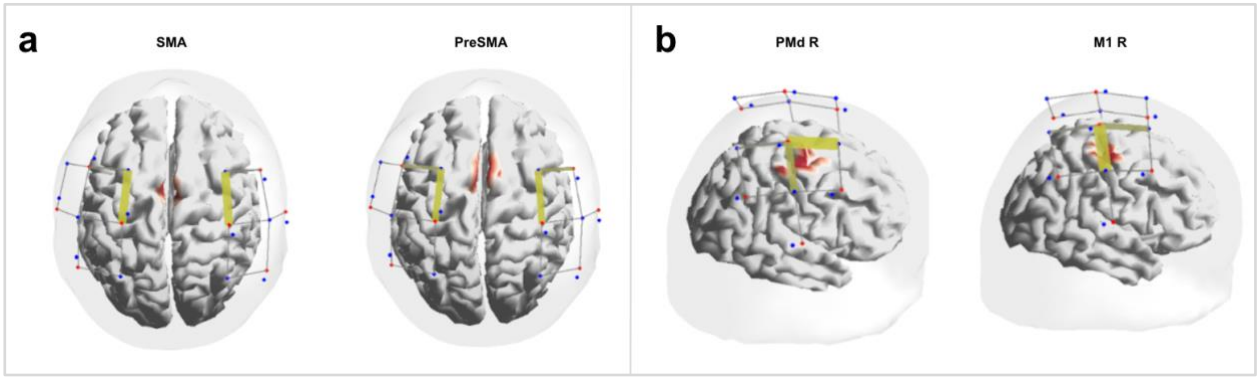

Figure 7. fNIRS Montage Detection Issues. Shaded red regions represent ROIs and yellow line thickness indicates the extent to which the source-detector channel was weighted in detecting the region's activity. (**a**) Difficulties in detecting preSMA and SMA activity. Visual inspection shows that channels used to infer activity do not sit directly above the desired regions. Significant distances between the ROIs and montage channels diminished the confidence that detected activity can be truly attributed to the preSMA and SMA. (**b**) Right PMd and right M1 detection overlap. Source-detector channels used to infer activity of both regions overlapped significantly due to optode sparsity, diminishing the confidence that the detected right M1 activity was accurately isolated.

Overall, our decision to employ the 8x7 motor montage was detrimental to our ability to adequately detect neural activity in our ROIs. The configuration's poor sensitivity for supplementary motor activity appeared to hinder its ability to detect an increase of SMA activity in response to a strong beat. Our faulty optode arrangement seems to also explain the reduced

activity detected in the preSMA during rhythms with strong beat, as it is apparent that this result is likely confounded by the activity of a variety of additional frontal regions (Herold et al., 2018). Finally, the sparsity of the chosen optode arrangement led to substantial overlap between the channels used to detect right M1 and right PMd activity. Because subjects were not moving during data collection it is unlikely that this activity can truly be attributed to the M1, perhaps instead suggesting that this result was due to a detection of PMd activity.

The Roles of the SMA and PMd in Beat Perception

Past experiments overwhelmingly support the role of both supplementary motor and premotor areas in human beat perception (Chen et al., 2008; Bengtsson et al., 2009; Grahn & Rowe, 2009; Teki et al., 2011; Kung et al., 2013). Importantly, both regions have been shown to display increased coupling to the basal ganglia during presentation of auditory rhythms (Grahn & Rowe, 2009). More specifically, the SMA has been implicated in processing sequence predictability and making temporal predictions (Bengtsson et al., 2009) – a finding that aligns with its displayed increase in activation to rhythms with salient beat (Grahn & Brett, 2007). Other studies have shown an increase in PMd-STG coupling during rhythm perception, suggesting a role in auditory-motor integration (Chen et al., 2008). Unlike the SMA, past studies do not show an elevation in premotor region activity during strong-beat rhythms (Grahn & Brett, 2007)

Taken together, theoretical models have implicated both the SMA and PMd in a striato-cortical network that mediates beat-based timing (Grahn & Rowe, 2009; Teki, 2011). The "Action Simulation for Auditory Prediction" (ASAP) hypothesis conjunctively emphasizes SMA-driven motor planning and premotor-driven auditory-motor connectivity in a comprehensive model of human beat perception (Patel & Iversen, 2014; Canon & Patel, 2020).

Our current study was unable to effectively detect activity from the SMA and preSMA, preventing our capacity to provide support for the established findings on their role in rhythm and beat perception. However, we can potentially ascribe the activity we supposedly retrieved from the right M1 instead to the right PMd. Making this attribution would indicate that premotor activity increased during rhythms with a strong beat in comparison to those lacking a strong beat. This finding does not align with past fMRI-based research (Grahn & Brett, 2007), but it may provide preliminary evidence of the PMd's role specifically in beat perception, rather than activating in response to all rhythms regardless of beat salience. Such a conclusion may point towards a more significant role of premotor areas within the current theoretical models of beat-based timing (Teki et al., 2011), but further research is needed to confirm this finding.

Conclusion

Our inability to replicate the findings of Grahn & Brett (2007) using fNIRS does not provide support for the imaging technique as a viable tool in future investigations of beat perception in cortical motor areas. However, this result appears to be explained by experimental error, and should not be ascribed to limitations of fNIRS as a technology. Although fNIRS' capacities in this field of research remain unknown, it is our expectation that future investigations with a better-informed methodological approach will confirm our hypotheses. The potential of the device to be effectively applied to the existing experimental paradigms of beat perception may be fulfilled by collecting sufficient baseline data, accounting for motion artifacts through extensive correction procedures, and employing a montage that optimizes the detection of activity from ROIs. fNIRS' permission of subject motion is a notable advantage for a field exploring music's connection to movement. While our findings do not directly support its utility, future investigations must continue to evaluate fNIRS' suitability with the current state of

research. The device's potential to contribute to investigations of beat perception, and to support new experimental methods within the broader field of music neuroscience, demonstrates its promise as an effective research tool in this field.

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