Multimodal interaction underlying piano playing-based rehabilitation

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Introduction

Playing a musical instrument implies the execution of sequences of movements accurately in time and spatially along the musical instrument, good motor coordination and the adjustment of finger movements according to auditory, visual and proprioceptive feedback. Underlying the multiplicity of abilities required for musical performance are multiple neuronal processes responsible for motor function and coordination but also a close interaction between motor and sensory neuronal mechanisms [1].

Importantly, music performance not only relies but also promotes a close communication between sensory and motor areas. Indeed, playing a musical instrument has been associated to differences in brain structure between a group of children that received piano training for 15 months and an age-matched control group without musical training [2]. Furthermore, several studies have shown how listening to musical rhythms elicits activity not only in auditory areas but also in motor areas of the brain [e.g. 3]. It is therefore reasonable to hypothesize that playing a musical instrument has the potential to reach and rehabilitate neuronal processes associated to motor function that have been affected by neuronal damage. Changes in motor-related brain activity have been reported in a group of patients with manual impairments caused by stroke that had received music-based therapy [4]. Similar changes were not observed in the control group that had received conventional therapy. The effectiveness of the training is believed to be determined by the direct auditory feedback received during music-based therapy.

Whether and how such benefits of music-based training can be achieved in patients with cerebral palsy (CP) is still a question requiring research. CP is a medical condition involving multiple disabilities, resulting from neuronal damage during development, pre- or perinatal. Whilst motor impairments form the main symptom of this condition, additional sensory and/or cognitive deficits may also occur that are linked to motor deficits. Recent studies investigating the effect of piano training in the development of hand motor function in youths with CP do suggest a positive effect of training [e.g. 5]. Nevertheless, further research is still needed to confirm and clarify how piano based training can foster manual function in patients with CP.

One aspect that needs clarification is the role of auditory-motor interactions in a potential effect of piano training. One way to investigate this is via a tapping task in that the tapping occurs synchronously to an external auditory beat. This is a relatively simple task that requires adjusting a motor response to an auditory stimulus and that can in principle be performed by the majority of patients with CP. In addition to this, electroencephalographic (EEG) recordings of brain activity during tapping to the beat can make visible evoked activity not only at the frequency of the auditory beat, but also at the frequency of tapping and at a frequency that is a combination of these two frequencies [6]. This latter evoked peak in the electroencephalogram is believed to reflect the integration of auditory and motor processes. That is, tapping to the beat can provide a means to investigate auditory-motor interaction by relating the frequencies of the auditory input stimulus with the frequency of the evoked brain activity, without the need for collecting behavioral measures. And this can be a useful experimental paradigm to investigate rehabilitation effects in a medical condition involving multiple disabilities. The results of a preliminary tapping test with two adults, one with CP and one healthy control are here presented.

Experimental Methods

Experimental procedure

There were three different experimental conditions:

a. Listening to an auditory rhythm, over headphones (Auditory beat condition);
b. One-finger tapping at a partial frequency of the auditory beat presented over headphones (Tapping-to-Beat condition);
c. One-finger tapping in the absence of an auditory beat (Spontaneous Tapping condition)

The tests were performed by two adult participants, one adult healthy control and one adult with bilateral CP, with the right side affected and with distonia. The patient is not able to walk and mobility is only possible with a wheelchair. Manual ability is affected in both hands, but strongly in the right side. Tests were performed with the left hand/finger.

Different auditory rhythms were presented to the two participants:

1. The healthy control was presented a 30-s long auditory stimulus consisting of a series of 500-Hz tones, 25-ms long including 5-ms up/down ramps, interspaced by 400-ms intervals. This stimulus was generated in MATLAB2015b® and presented over headphones. In the Tap-to-Beat condition, the participant was asked to tap

with every second beat, that is, with an ‘optimal’ Inter-Tap-Interval (ITapI) of 800-ms. Tapping was done at a electric piano keyboard. All three conditions (a., b. and c.) were repeated six times.

2. The auditory beat presented to the participant with CP was a standard 120-beats-per-min metronome, delivered by a CASIO electric piano and presented over headphones. The participant was asked to tap only with every fourth beat, that is, every 2000-ms, in the same electric piano used to present the metronome. This stimulus and task were adopted because they were easier to perform for the participant. Each condition lasted two minutes approximately and all three conditions were repeated two to three times.

For both participants, tapping to the beat and spontaneous tapping was done with one finger on an electric piano. The patient tapped with his best hand, the left. Tapping times were recorded digitally via a MATLAB® MIDI interface with data sets containing information about the keys struck and the times of onset and offset keystrokes relative to the initialization of the interface.

The EEG was recorded for each of the three conditions with an 8-channel ENOBIO system (Neuroelectrics®), using conducting gel or conducting gel pads, from the following locations of the 10/20 system: Fp1, T7, T8, C3, Cz, C4, Fz, Pz. The reference was set to the left earlobe and the signal sampled at 500-Hz.

Data analysis

ITapIs were extracted by subtracting the onset times of consecutive keystrokes. All ITapI values were then converted into angles in radians in order to apply circular statistics and to represent the collected data on an unit circle. Tapping accuracy was obtained by computing the resulting mean vector over all angle points and tapping consistency by computing circular variance. All calculations were performed and plots obtained using the CircStat2012a Toolbox for MATLAB [7] running under MATLAB 2015b®.

Continuously recorded EEG signals were processed using the EEGLAB toolbox for MATLAB [8] and analyzed with MATLAB2015b®. The following preprocessing steps were applied to each EEG recorded signal: 1) baseline removal, 2) low-pass filtering at 40-Hz, 3) high-pass filtering at 0.1-Hz. Further data analysis was similar to that described in previous works [6]. The initial seconds of the preprocessed signals were excluded from further analysis to avoid the influence of transient auditory evoked potentials. This signal was then divided into 28s-long epochs and the average across the different segments computed. The power spectral density (PSD) of the resulting 28-s long average signal was obtained using the Welch method (function *pwelch* in MATLAB2015b).

Results

Figure 1 shows the circular distribution of tap onsets when participants tapped to the external beat, the second experimental condition. The distribution of points around 0-rad indicates that both the control participant as well as the patient with CP did not tap in a random way (in which case points would be distributed all around the circle) but did follow the external rhythm. Tapping was more variable for the patient with CP, with a circular variance of 0.117 relative to 0.022 for the healthy control. This larger variance indicates difficulty in following the beat.

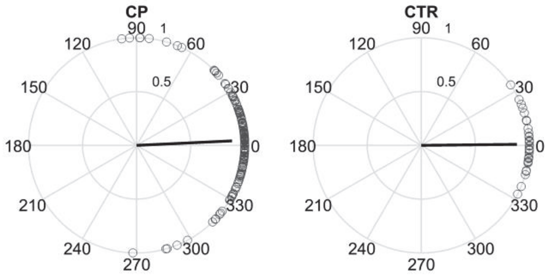

Figure 1: Circular distribution of ITapI, in radians, when the participant was tapping following the auditory beat. ‘CP’/ ‘CTR’ indicate results obtained for the patient with CP and the control participant respectively. Also represented in each plot is the mean resulting vector. A tap occurring exactly at the time instant of the auditory beat would yield a dot at 0-rad, a tap lagging behind/occurring earlier than the beat would yield a data point in the upper/lower part of the circle respectively.

For the patient with CP this ability to tap in a regular and consistent way diminished when the external beat was absent. As illustrated in Figure 2, when this participant was asked to tap spontaneously as regularly as possible, the mean ITapI was shorter relative to the interval set by the external beat, and ITapIs were more variable (i.e. larger coefficient of variation CV). The control participant however was able to keep a similar tapping rhythm as well as keeping a low CV of ITapI.

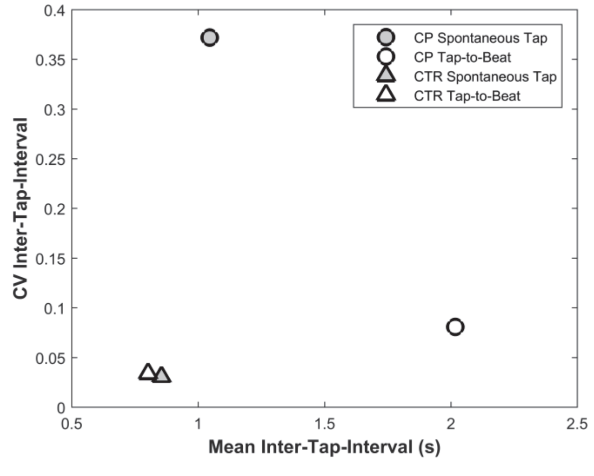

Figure 2: Coefficient of variation of Inter-Tap-Interval

(ITapI) as a function of the mean ITapI in seconds, for the patient with CP (circles) and for the control participant (triangles). Filled symbols illustrate results obtained when participants tapped spontaneously, without following an external beat, and the open symbols when participants tapped synchronously to the external beat.

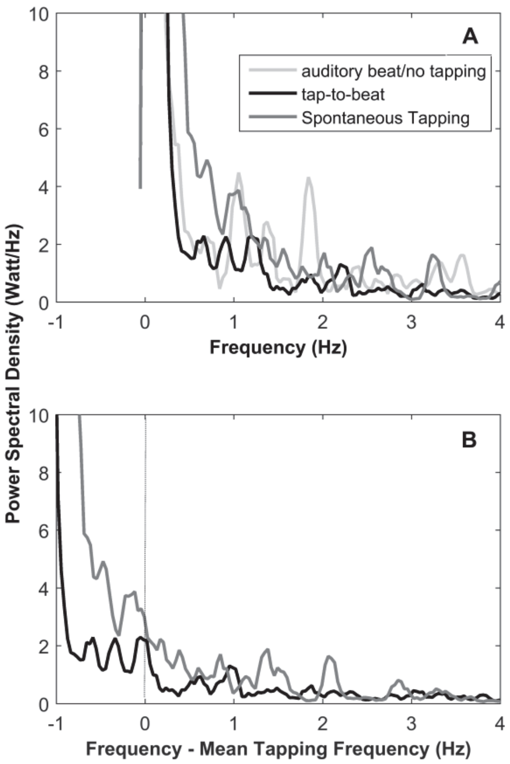

Figure 3A: Power Spectral Density (PSD) of EEG signals recorded from the control participant during: 1) spontaneous tapping (dark grey line), 2) tapping to the beat (black line) and 3) when listening to the auditory beat stimulus (light grey line). Each line represents the average PSD computed across the following electrode locations: T7, T8, C3, Cz and C4. **B**: As in **A.** but the frequency axis is aligned to the mean tapping frequency computed from the kinematic data in each experimental condition.

The power spectral density of brain activity recorded with the EEG during tapping is illustrated in Figures 3 and 4 for the control participant and for the patient with CP respectively. The same data is represented in both panels A and B, the difference being that in panels B the frequency axis is aligned to the mean tapping frequency computed directly from the keystroke timings for each condition. This latter representation facilitates the observation of a peak at 0-Hz, that is, at the mean tapping frequency. This peak reflects therefore brain activity that is associated to the tapping movement. Both for the control person (figure 3B) as well as for the patient with CP (figure 4B) there is activity when participants tapped to the external beat (black lines) and when they tapped spontaneously, even though the peak is much smoother in the latter case, especially for the patient with CP. Given that for the patient the tapping frequency (or its inverse, ITapI) in the tapping-to-beat condition (f=0.5Hz, ITapI=2s) was lower (i.e. ITapI larger) than in the spontaneous tapping condition (f=0.96 Hz; ITapI=1.05s), the peaks shown are indeed elicited by the tapping movement. These peaks are far apart when represented in a 'standard' frequency axis, not aligned to the tapping frequency as in Figures 3A and 4A. Also for the control participant a peak was observed at the tapping frequency both for the spontaneous tapping (f=1.16 Hz, ITapI=0.86 s) and tapping-to-beat conditions (f=1.20 Hz, ITapI=0.80 s). In this case tapping frequencies were identical for the two experimental conditions. A peak at 1.2-Hz can also be seen in the PSD obtained when the control participant did not tap and only listened to the auditory beat stimulus (light grey line in figure 3A). An equivalent peak is however not visible in figure 4A.

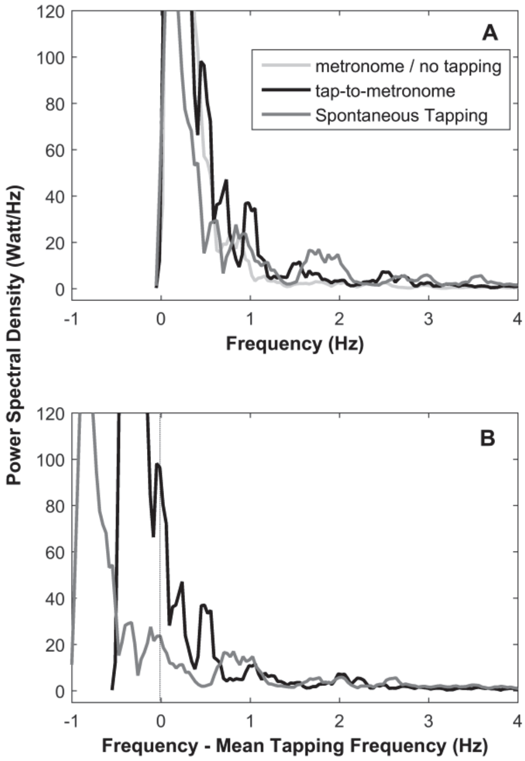

Figure 4A: PSD of EEG signals recorded from the patient with CP during: 1) spontaneous tapping (dark grey line), 2) tapping to the metronome (black line) and 3) when listening to the auditory beat stimulus (light grey line). Each line represents the average PSD computed across the following electrode locations: T7, T8, C3, Cz and C4. **B.** As in **A.** but the frequency axis is aligned to the mean tapping frequency.

Discussion

Results show that the patient with CP was able to tap consistently and follow the external auditory beat (Figure 1). Tapping to the beat was more regular, that is, had a lower coefficient of variation, relative to the spontaneous tapping when the external beat was present (Figure 2). Even though these are results from a single patient, they show that this participant was able to shape its motor action according to an external auditory stimulus. This suggests that tasks combining auditory and motor processes might be useful for the development of motor abilities.

The observation of peaks in the PSD of the EEG that are associated to the tapping movement, opens the possibility of using this method to investigate the role of auditory-motor interactions in motor training. The wider and smoother peak observed for the spontaneous tapping condition may reflect the larger variability in tapping performance. This was particularly visible in the results for the patient with CP. Activity reflecting the interaction between auditory and motor processes, as reported in previous studies [6], was here not possible, due to differences in the auditory stimuli used and in the experimental task. Observation of this type of brain activity however may also require a large data sample to get a better signal-to-noise ratio. The preliminary results presented here need therefore to be considered with caution but they still support the use this simple paradigm to investigate the role of auditory-motor interactions in music-based training in CP. It should be noted that the presence of multiple disabilities in CP, and namely of cognitive impairments limits strongly the range of experimental tests that can be carried out in this clinical group.

Acknowledments

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