ELSEVIER

International Journal of Psychophysiology 44 (2002) 177–184

INTERNATIONAL JOURNAL OF PSYCHOPHYSIOLOGY

www.elsevier.com/locate/ijpsycho

Musical beat influences corticospinal drive to ankle flexor and extensor muscles in man

Emily M.F. Wilson, Nick J. Davey*

Division of Neuroscience and Psychological Medicine, Imperial College School of Medicine, Charing Cross Hospital, London W6 8RF, UK

Received 21 August 2001; received in revised form 23 October 2001; accepted 29 November 2001

Abstract

Body movements in man are frequently observed in relation to musical rhythms. In this study we have investigated the effect of strongly rhythmic music on corticospinal drive to the ankle extensor and flexor muscles involved in foot tapping. Surface electromyographic (EMG) recordings were made from *tibialis anterior* (TA) and *lateral gastrocnemius* (LGN) muscles in 12 normal subjects. Rock music with a strong rhythmic beat or white noise was played. Transcranial magnetic stimulation (TMS) was delivered to the motor cortex in time with the music to produce motor evoked potentials (MEPs) in both muscles while relaxed. During white noise trials nine subjects showed a significant correlation of MEP areas in TA with LGN, compared with only three subjects during music. Overall, there was a significant decrease in the correlation coefficient during music. We conclude that correlated variations in MEP areas between the muscles seen during white noise can be destroyed in the presence of music. This may be due to subthreshold variations in corticospinal excitability to ankle extensors and flexors, which are time-locked to the musical beat but out of phase with one another.

Keywords: Magnetic stimulation; corticospinal system, music, rhythm

1. Introduction

Musical rhythm clearly has a very strong link with the motor system in man. When sitting idly listening to rhythmic music, it is often very difficult to suppress the natural urge to tap the feet or strum the fingers along with the beat of the music. Thaut et al. (1999) suggest that enhancement of motor function by auditory rhythms might be an evolutionary advantage as it may help to entrain motor tasks in the time domain. They further point out that more autonomic functions, such as the cardiac system, do not entrain to auditory rhythms; such an entrainment would have no advantage and might even be disadvantageous. However, other work has revealed that music with a slow relaxing tempo can increase the heart rate during treadmill exercise leading to increased endurance (Copeland and Franks, 1991).

*Corresponding author. Tel.: +44-20-8846-7284; fax: +44-20-8846-7338.

E-mail address: n.davey@ic.ac.uk (N.J. Davey).

0167-8760/02/$ - see front matter
PII: S0167-8760(01)00203-3

It is well known that repetition of a motor tasks improves performance (Hummelsheim, 1999). A functional MRI study (Krings et al., 2000) has shown that long-term motor practice in professional piano players can lead to a reduced degree of cortical activation of cortical motor areas than in control subjects. Clearly the auditory rhythmicity that is linked to this task may enhance this process of brain plasticity. Musical rhythm is commonly used to enhance training protocols in gymnasiums. A study to reinforce dry-land training procedures in competitive swimmers (Hume and Crossman, 1992) has shown that musical rhythm can be a beneficial in enhancement of routine exercise regimes. Another study (Metesdorf, 1994) has shown musical tempo to be important in exercise on a cycling ergometer whether internally driven by feedback, or whether external. Young women were found to have improved psychomotor function and mood together with decreased attention reaction time on nights when they had spent the night in a disco compared with a control night (Saletu et al., 1982). Furthermore, learning techniques that use the musical rhythm and movement can improve memory retention (Boykin and Allen, 1988).

Work by Altenmuller (1986) suggests that, unlike language processing, music processing may not be dominant in one cerebral hemisphere. The difference in processing may allow music to be considered an alternative channel of communication in rehabilitation (Borchgrevink, 1993), particularly in lateralised motor control deficits such as stroke. Indeed, one study concludes that music enhances the general mobility and social interaction of patients who have sustained cerebrovascular accidents (Cross et al., 1984). Two other studies have successfully used music to rehabilitate gait patterns (McIntosh et al., 1997) and general motor and emotional state (Pacchetti et al., 2000) in patients with Parkinson's disease.

Corticospinal excitability to different limb muscles is often correlated in relaxed individuals (Ellaway et al., 1998). If rhythmic music has an effect on the motor cortex which tends to induce alternating tapping movements in the feet, then such a correlation may be disrupted and break down while listening to music with a strong rhythmic beat. The hypothesis of this study is that TMS of the motor cortex may reveal less correlated, and maybe even alternating, excitability patterns in corticospinal pathways to ankle flexors and extensors while relaxed and listening to rock music with a strong beat.

2. Methods

2.1. Subjects

Twelve normal subjects (ages 21–32 years; nine male; two left-handed) were recruited for study. None had ever been suffered from a neurological or psychological disorder and none was taking medication. All subjects gave informed written consent. Ethical approval for the study was obtained from the Riverside Research Ethics Committee.

2.2. Electromyographic (EMG) recordings

Surface electromyographic (EMG) recordings were made from the *tibialis anterior* and *lateral gastocnemius* muscles of the dominant leg. Self-adhesive Ag/AgCl surface electrodes (Arbo Neonatal Blue; 2 cm diameter) were positioned using palpation over the belly of each muscle. The electrode pairs were positioned in parallel to the long axis of the muscles. EMGs were filtered (± 3 dB below 100 Hz and above 2 kHz) and amplified ($\times 1000$) before being sampled (4000 samples/s) by a computer for storage and analysis (Cambridge Electronic Design 1401, SIGNAL software, IBM compatible PC).

2.3. Transcranial magnetic stimulation (TMS)

Transcranial magnetic stimulation was delivered to the motor cortex using a MagStim 200 stimulator connected to an angled double-cone stimulating coil (maximum magnetic field strength 1.4 Tesla) with its cross-over centred over the vertex and the induced current flowing in a posterior to anterior direction in the brain. The stimulus intensity was increased in steps of 1% maximum stimulator output (% MSO) until motor evoked potentials (MEPs) were produced in response to

at least five out of 10 stimuli with both muscles relaxed. This intensity was designated threshold (T). Experimental trials were conducted using a stimulus intensity equivalent to $1.2 \times T$.

2.4. Protocol

Subjects were seated comfortably on an upright chair. Trials consisting of 50 magnetic stimuli were conducted while taped music or white noise was played at a peak volume of 98 dB. White noise was recorded onto cassette tape from an un-tuned FM radio. In the music trials, rock music [*Breathe* from the album *Fat of the Land* by Prodigy (XL/ Maverick records; 1997)] with a strong rhythmic beat was used. When this was sampled and examined on computer; the beat was approximately 2 Hz. In the music trials, an operator, keeping time with the music, activated the magnetic stimulator remotely on the beat. The stimulator trigger time was examined with reference to the music and was found to occur between 50 and 100 ms in advance of the middle of the drum burst of each beat. A clock circuit (Digitimer D 4030) was used in some trials to delay the stimulus by 250 ms so that it was delivered between beats. During the white noise trials the stimuli were delivered randomly. In all trials the stimuli were delivered with an inter-stimulus interval of between 3 and 6 s. This time interval allowed for the magnetic stimulator to recharge and so stimuli were not delivered with respect to every successive musical beat. As a result, each trial of 50 stimuli lasted between 4 and 5 min. Trials were conducted during active foot tapping to the beat of the music and while completely relaxed. A practice trial was conducted initially to allow individuals to become accustomed to the foot-tapping task.

In order to avoid any effects of practice resulting from the active trials, the same trial order was used in all subjects. We were confident in using this experimental design as there is no reported progressive change in the character of MEPs either within trials or between subsequent trials (see Ellaway et al., 1998). The following order of trials was used. The interval between trials was 3–5 min.

1. Practice foot-tapping to the music with no TMS, for approximately 2 min.
2. TMS (50 stimuli) during white noise, muscles relaxed.
3. TMS (50 stimuli) during music, delivered on the beat, muscles relaxed.
4. TMS (50 stimuli) during music, delivered midway between beats with muscles relaxed.
5. TMS (50 stimuli) during music, delivered on the beat, with active foot-tapping.
6. TMS (50 stimuli) during music, delivered midway between beats with active foot-tapping.

2.5. Analyses

The 50 MEPs in each trial were rectified and averaged using a signal averaging software package (Cambridge Electronic Design, SIGNAL). Cursors were set at the start and end of the averaged MEP; using these cursor positions the area of each individual MEP in the trial was measured. The areas of the 50 MEPs from *tibialis anterior* were plotted against the areas of the 50 MEPs from *lateral gastrocnemius*, evoked in the same trial, on a stimulus by stimulus basis. Regression analysis was performed, the correlation coefficient (R^2) calculated and the number of individuals with significant correlations for each trial-type were counted. Chi-squared tests were used to assess any differences in the number of significant correlations. The variability of MEP areas [Coefficient of Variation (C of V)], in each muscle in each trial of 50 MEPs was calculated. Mean MEP areas and C of Vs of MEP areas were compared between the different trials of 50 MEPs using Student's paired t-tests. The level of significance throughout was taken as $P < 0.05$.

3. Results

3.1. MEP area and variability

There was no difference in mean area between the different trials (Student's paired t-test; $P > 0.05$) with the muscles relaxed. During active foot-tapping mean ($\pm$S.E.M.) MEP areas were significantly facilitated ($P < 0.01$) in TA compared with the relaxed white noise trial (0.0017 ± 0.0003

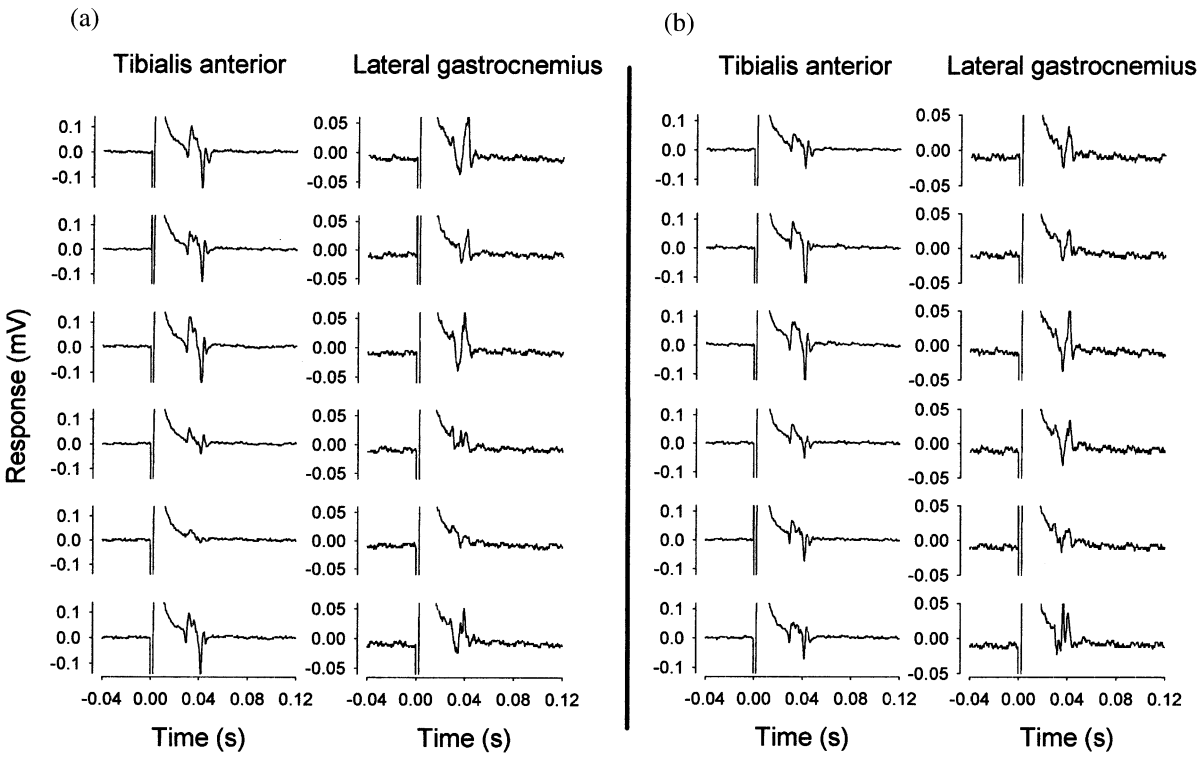

Fig. 1. Series of six sequential MEPs from *tibialis anterior* and *lateral gastrocnemius* muscles. The MEPs in (a) are part of a trial conducted during white noise. The MEPs in (b) were evoked by TMS delivered midway between musical beats with both muscles relaxed. Both sets of MEPs are from the same individual (KA). There is a tendency for MEPs in TA and LGN to show correlation in their amplitudes during white noise (a); this is less evident during music (b).

mV ms) whether TMS was delivered on the beat (0.0049 ± 0.00097 mV ms) or midway between beats (0.0068 ± 0.0012 mV ms). In LGN, MEPs were significantly ($P < 0.05$) facilitated when TMS was delivered on the beat (0.0014 ± 0.00052 mV ms) but not significantly ($P > 0.05$) when delivered between beats (0.0017 ± 0.002 mV ms) compared with the relaxed white noise trial (0.00078 ± 0.00026 mV ms).

Coefficient of variation (C of V) of the areas of MEPs were calculated for each individual in each trial of 50 MEPs. When compared across subjects (paired *t*-test) there was no significant ($P > 0.05$) difference in the C of V of MEP areas, between the white noise trial and any other trial.

3.2. Linear regression analyses

Fig. 1 shows a sequence of 6 MEP responses in TA and LGN during a white noise trial (a) and during a relaxed music trial in the same subject (subject KA) with application of TMS midway between beats (b). Visual inspection of MEPs from the white noise trial suggests that there may be some correlation of amplitudes between the two muscles. In the music trial there is no suggestion of such correlation.

When linear regression analyses were performed on the data, nine of the twelve subjects showed significant ($P < 0.05$) correlation between the areas of MEPs from TA and from LGN during the white noise trial. When TMS was delivered between beats in relaxed music trials, only three subjects showed significant correlation between MEP areas in the two muscles. A chi-squared test showed this change was greater than expected by chance ($P < 0.05$).

Data from the nine individuals that showed no correlation when TMS was applied midway

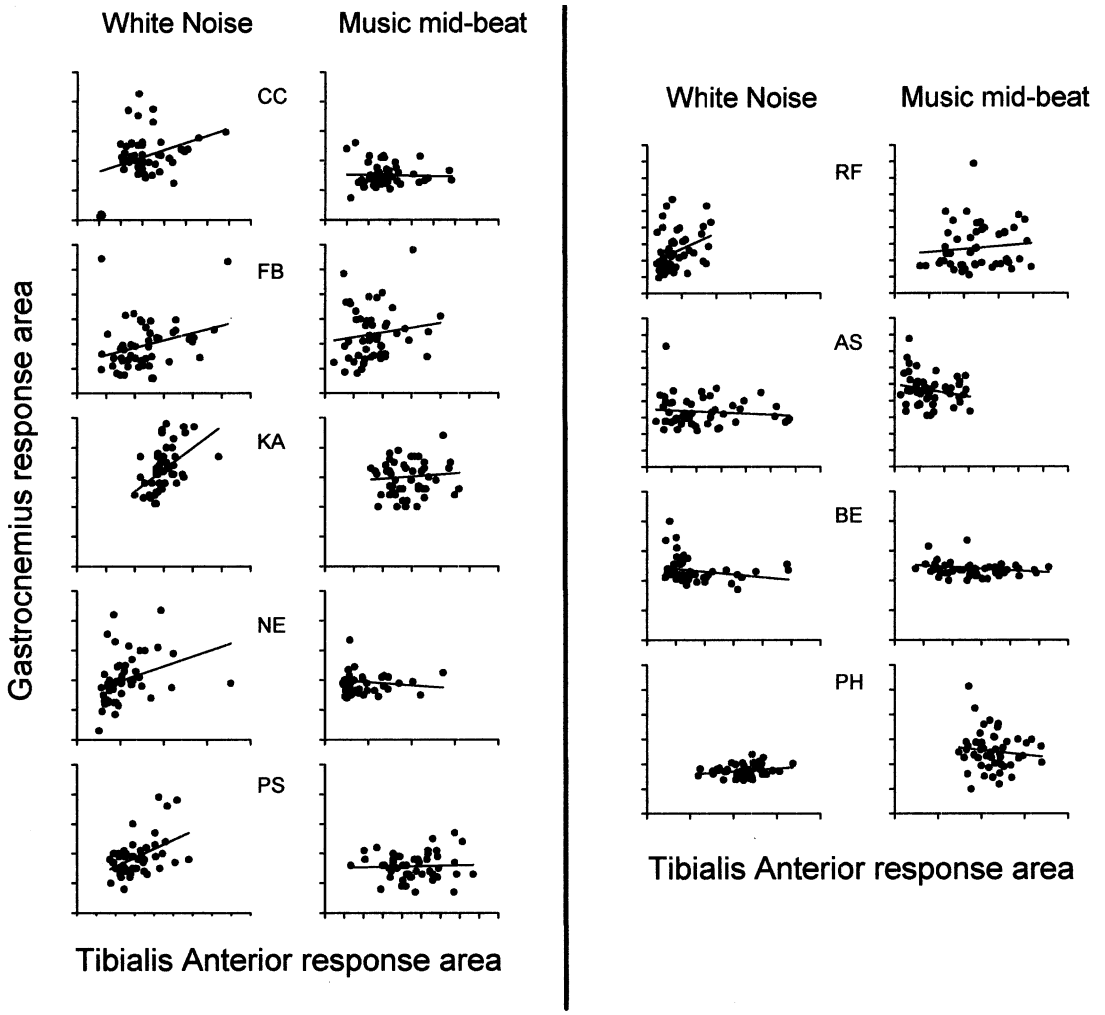

Fig. 2. Correlations between areas of MEPs in *tibialis anterior* muscle and *lateral gastrocnemius* muscle to TMS of the motor cortex. The left hand graph in each pair was constructed from data collected during white noise; the right hand graph was constructed from data collected during music when TMS was delivered midway between beats. Muscles were relaxed in both trials. The nine subjects illustrated showed no significant ($P > 0.05$) correlation between the two muscles during the music. Each pair of graphs is plotted using the same axis scales.

between beats during relaxed music trials are shown in Fig. 2. Six of these subjects showed significant correlation during white noise trials which was destroyed during the music trials, the other three (AS, BE, PH) showed no correlation during white noise.

Three other subjects continued to show correlation during the relaxed music trials with TMS delivered midway between beats. These three subjects are shown in Fig. 3. Two of these three subjects (MC and NW) showed reduced correlations during the music trials with R^2 dropping from 0.43 to 0.09 and from 0.22 to 0.09, respectively. The third subject (JR) showed no reduction in correlation during the music trial, in fact the R^2 value for this subject rose slightly from 0.27 to 0.29 during the music. The mean ($\pm$S.E.) R^2 value across all subjects decreased from

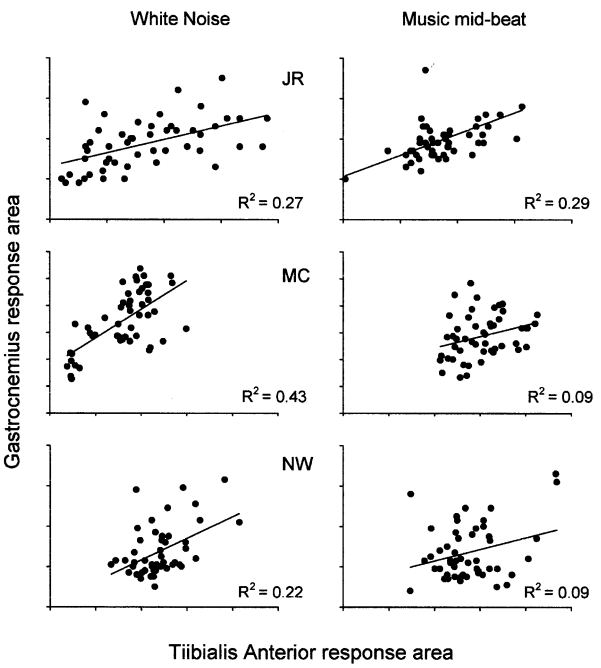

Fig. 3. Correlations between areas of MEPs in *tibialis anterior* muscle and *lateral gastrocnemius* muscle to TMS of the motor cortex. The left hand graph in each pair was constructed from data collected during white noise; the right hand graph was constructed from data collected during music when TMS was delivered midway between beats. Muscles were relaxed in both trials. The three subjects illustrated showed significant ($P<$ 0.05) correlation during the music trial. In two subjects (MC, NW) the correlation was reduced during music compared with the white noise trial. Each pair of graphs is plotted using the same axis scales.

0.161 ± 0.03 in white noise trials to 0.049 ± 0.02 during music (paired *t*-test; $P<0.05$).

A similar pattern was seen in trials where TMS was delivered on the beat during relaxed music trials. Three subjects (JR, KA, NW), two of whom showed correlation when TMS was delivered midway between beats, continued to display significant correlation. In these three individuals correlation coefficients (R^2) rose in two individuals compared with the white noise trial (JR from 0.27 to 0.58; NW from 0.22 to 0.29) while it remained constant in the third (KA remained at 0.24).

Less consistent effects were seen when TMS was applied during active foot-tapping trials. When TMS was delivered on the beat two individuals (FB and KA) displayed a negative correlation suggesting that small MEPs in TA were associated with large MEPs in LGN. These same two individuals showed negative correlations when TMS was delivered midway between beats in active tapping trials. Both subjects showed significant positive correlations when TMS was delivered during white noise trials. Data from these subjects are shown in Fig. 4. The three graphs are plotted on the same scale and it is clear that the MEPs in both muscles are facilitated during the active-tapping trials.

Two individuals (BE, JR) showed significant positive correlations during on the beat TMS active tapping trials. Four individuals (JR, MC, NE, PH) showed significant positive correlations when TMS was delivered midway between beats in the active foot-tapping trials.

4. Discussion

In this study we reasoned that the corticospinal drive to the ankle dorsi-flexors and extensors (*tibialis anterior* and *lateral gastrocnemius*) might show rhythmic corticospinal facilitation and perhaps inhibition during music which might, if permitted, have induced subjects to tap their feet. MEP responses become larger when corticospinal drive is increased during voluntary contraction of the target muscle (Lemon et al., 1986; see Rothwell et al., 1991), when the contralateral homonymous or heteronymous muscles are contracted (Stedman et al., 1998), preceding a simple reaction task (Davey et al., 1998) and during non-specific actions such as sticking out the tongue (Hufnagal et al., 1990). In addition to these factors, other synaptic inputs to the corticospinal system result in a degree of variability in the area of MEPs produced to a series of magnetic stimuli of the same strength (Ellaway et al., 1998). We found no overt change in the mean area of MEPs evoked by TMS at different times during the beat with the muscles relaxed. Neither did we find any change in the variability of MEP areas.

When the subjects were foot-tapping to the music the drive to both TA and LGN was increased but waxing and waning with the phase of the task. During this task MEPs in both muscles were

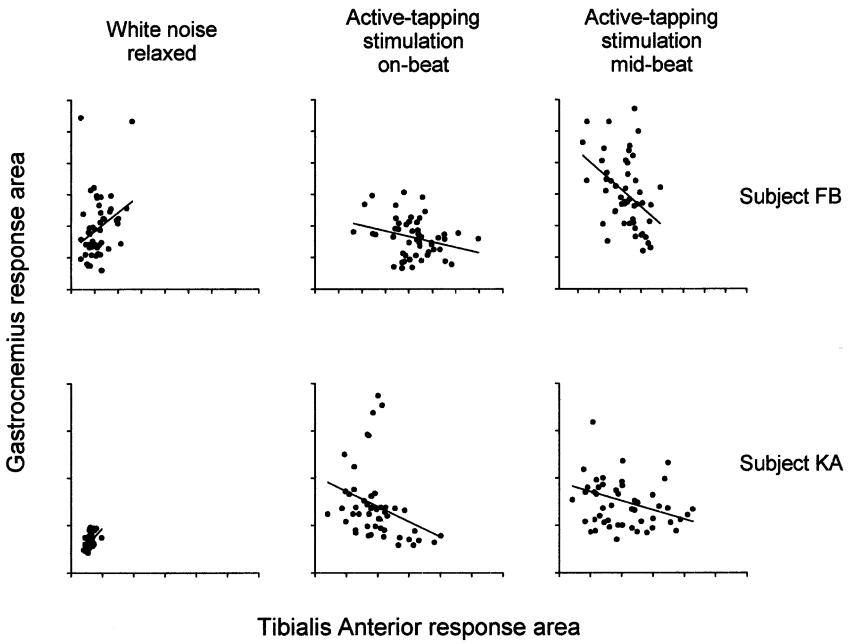

Fig. 4. Correlations between areas of MEPs in *tibialis anterior* muscle and *lateral gastrocnemius* muscle to TMS of the motor cortex. In the left hand graphs, both individuals show significant ($P<0.05$) positive correlations during while noise with both muscles relaxed. The other four graphs were constructed while subjects tapped their foot in time with the musical beat. Data in the centre graphs were produced with TMS delivered on the beat and data in the right hand graphs were produced with TMS delivered midway between beats. Both subjects show significant ($P<0.05$) negative correlations during active foot tapping trials.

facilitated. In TA, TMS delivered both on the beat and midway between beats produced facilitated MEPs whereas only the on-beat trials showed facilitated MEPs in LGN. Examination of the raw EMG during foot-tapping showed that bursts of activity in TA (when the foot was dorsi-flexed) were longer than in LGN, so both timings of TMS delivery could catch TA with increased drive. The LGN bursts were much shorter making it less likely that TMS would be delivered during its active phase in the task. The MEP facilitation seen during active foot-tapping may therefore be explained by an increased corticospinal drive to the muscle at the time of TMS delivery.

Although the musical rhythm was not changing the overall excitability level of the corticospinal system, it is possible that the pattern of background excitability change might alter with beat. In relaxed individuals, one characteristic of MEPs is that, although they vary in area from stimulus to stimulus, there is correlation of MEP area between different muscles (Ellaway et al., 1998). During active foot-tapping the asynchronous activation of TA and LGN can destroy this correlation and, on occasions, generate a negative correlation (see Fig. 4).

Nine out of 12 subjects showed significant correlation of MEP areas during white noise and only three out of twelve when TMS was applied midway between beats during music with the muscles relaxed. Of these three subjects, two showed a reduced correlation during the music. If there are subliminal, but rhythmic, changes in corticospinal drive to TA and LGN during music while the subject is relaxed, then this might manifest itself in rhythmic changes in MEP areas. Since in a foot-tapping task TA and LGN are activated out of phase with one another, any correlation of MEP areas seen during white noise may be obliterated or reduced during the music.

These results indicate that strong rhythmic music can influence the corticospinal system, even when

the subject is asked to remain relaxed. This might help to explain why music improves exercise training regimes (for example, Hume and Crossman, 1992) and helps improve motor recovery in Parkinson's disease (Pacchetti et al., 2000) or following stroke (Cross et al., 1984). It would be of interest to examine whether individuals trained in rhythmic movements (for example dancers) show a more pronounced link between musical rhythm and motor output. Further investigation is required to elucidate whether there are more effective beat frequencies and the importance of tonal qualities and familiarity with the tune.

Acknowledgments

We gratefully acknowledge operational help with the experimental trials from Dr Paul Strutton, Mr Anil Sahal and Mrs Maria Catley.

References

Altenmuller, E., 1986. Brain electrical correlates of cerebral music processing in the human. Eur. Arch. Psychiatry Neurol. Sci. 235, 342–354.

Borchgrevink, H.M., 1993. Music, brain and medicine. Tidsskrift Norske Laegeforen. 113, 3743–3747.

Boykin, A.W., Allen, B.A., 1988. Rhythmic-movement facilitation of learning in working-class Afro-American children. J. Genet. Psychol. 149, 335–347.

Copeland, B.L., Franks, B.D., 1991. Effect of types and intensities of background music on treadmill endurance. J. Sports Med. Phys. Fitness 31, 100–103.

Cross, P., McLellan, M., Vomberg, E., Monga, M., Monga, T.N., 1984. Observations on the use of music in rehabilitation of stroke patients. Physiother. Can. 36, 197–201.

Davey, N.J., Rawlinson, S.R., Maskill, D.W., Ellaway, P.H., 1998. Facilitation of a hand muscle response to stimulation of the motor cortex preceding a simple reaction task. Motor Control 2, 241–250.

Ellaway, P.H., Davey, N.J., Maskill, D.W., Rawlinson, S.R., Lewis, H.S., Anissimova, N.P., 1998. Variability in the amplitude of skeletal muscles responses to magnetic stimulation of the motor cortex in man. Electroenceph. clin. Neurophysiol. 109, 104–113.

Hufnagal, A., Jaeger, M., Elger, C.E., 1990. Transcranial magnetic stimulation: specific and non-specific facilitation of motor evoked potentials. J. Neurol. 237, 416–419.

Hume, K.M., Crossman, J., 1992. Musical reinforcement of practice behaviours among competitive swimmers. J. Appl. Behav. Anal. 25, 665–670.

Hummelsheim, H., 1999. Rationales for improving motor function. Curr. Opin. Neurol. 12, 697–701.

Krings, T., Topper, R., Foltys, H., et al., 2000. Cortical activation patterns during complex motor tasks in piano players and control subjects. A functional magnetic resonance imaging study. Neurosci. Lett. 278, 189–193.

Lemon, R.N., Mantel, G.W., Muir, R.B., 1986. Corticospinal facilitation of hand muscles during voluntary movement in the conscious monkey. J. Physiol. 381, 497–527.

McIntosh, G.C., Brown, S.H., Rice, R.R., Thaut, M.H., 1997. Rhythmic auditory-motor facilitation of gait pattern in patients with Parkinson's disease. J. Neurol. Neurosurg. Psychiatry 62, 22–26.

Metesdorf, F.L., 1994. Cycle exercising in time with music. Perceptual Motor Skills 78, 1123–1141.

Pacchetti, C., Mancini, F., Aglieri, R., Fundaro, C., Martignoni, E., Nappi, G., 2000. Active music therapy in Parkinson's disease: an integrative method for motor and emotional rehabilitation. Psychosom. Med. 62, 386–393.

Rothwell, J.C., Thompson, P.D., Day, B.L., Boyd, S., Marsden, C.D., 1991. Stimulation of the human motor cortex through the scalp. Exp. Physiol. 76, 159–200.

Saletu, B., Schultes, M., Grunberger, J., 1982. Influence of the disco-scene on the psyche and soma of young people: psychometric, computerised-EEG and physiological studies. Wiener Med. Wochenschr. 132, 137–143.

Stedman, A., Davey, N.J., Ellaway, P.H., 1998. Facilitation of human first dorsal interosseus muscle responses to transcranial magnetic stimulation during voluntary contraction of the contralateral homonymous muscle. Muscle Nerve 21, 1033–1039.

Thaut, M.H., Kenyon, G.P., Schauer, M.L., McIntosh, G.C., 1999. The connection between rhythmicity and brain function. IEEE Eng. Med. Biol. Mag. 18, 101–108.